AN243

Fundamentals of the Infrared Physical Layer

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INTRODUCTION

Infrared light, commonly referred to as "IR", is a common, easy-to-use, low power and low-cost media to transmit information. Among the few "wireless" communication choices, IR has the significant advantage of compatibility with hundreds of millions of electronic devices with IR ports (i.e., laptop PCs, PDAs).

The vast majority of IR-capable devices are compatible with a set of standards established by the Infrared Data Association, or IrDA®. These standards include guidelines for implementing the IR Physical Layer (IrDA Serial Infrared Physical Layer specification), ensuring that IR communication can be established through free space between two dissimilar devices.

This document describes the fundamentals of the infrared physical layer, the IrDA standard and selecting the proper discrete emitter and photodiode components for circuit implementation.

FUNDAMENTALS

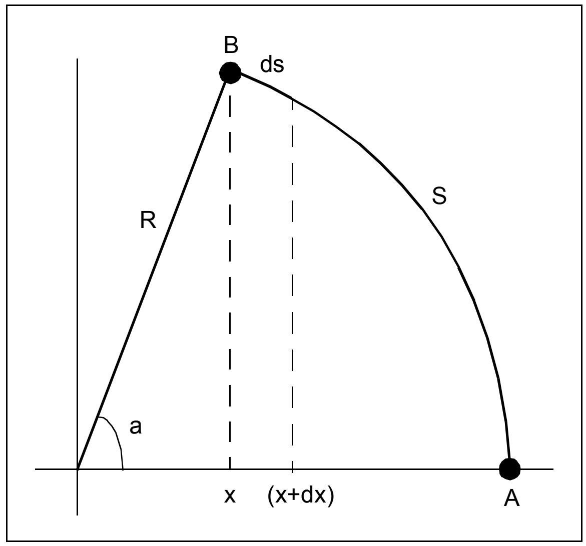
To better understand the design requirements of an IR application, one needs to understand the fundamental behavior of the components.

The Steradian

IR behavior can be predicted more easily than can RF behavior. The devices that emit and detect IR are very simple. The challenge to the designer is to predict how much energy is available from which the information may be extracted. RF designers are familiar with the concept of a "Link Budget". This simple method starts with how much energy is put into the air and is attenuated by the inverse-square ratio, leaving a minimum signal level for the receiving circuit to detect. The Link Budget for IR is handled in the same way. The unit measure of energy in IR is mW/Sr, with 'Sr' being the abbreviation for steradian. Understanding the steradian is key to planning for the energy available in the application.

To understand the steradian, we will first consider the radian. The radian is defined as the angle 'a' that produces an arc 'S' that is equal in length to the radius 'R' and is equal to 360/2π degrees (~ 57° 17' 46.6"). The arc is created by moving the radius arm from point A to point B at the given angle, as shown in Figure 1. There are 2π radians in a circle.

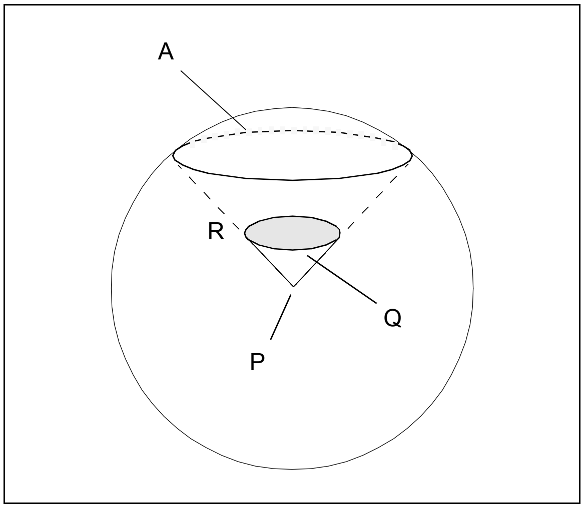
FIGURE 1: ARC DESCRIBED BY A RADIAN



The steradian is defined as conical in shape, and is the Standard International (SI) unit of solid angular measure. It may be examined by rotating the arc 'S' (from Figure 1) around the X-axis. The resulting area is a part of the surface of a sphere, as shown in Figure 2, where point 'P' represents the center of the sphere.

The solid (conical) angle 'Q', representing one steradian, is such that the area 'A' of the subtended portion of the sphere is equal to R^2, where 'R' is the radius of the sphere. There are 4π, or approximately 12.57 steradians, in a complete sphere.

FIGURE 2: AREA DESCRIBED BY A STERADIAN



Calculating the exact area swept out by a steradian is much like calculating the area of a sphere. Referring back to Figure 1, the area swept out by rotating arc 'S' around the x-axis may be found as follows:

$$F(x) = \sqrt{(R^2) - (x^2)}$$ Function for the arc

$$f(x) = \left[-\frac{x}{\sqrt{(R^2) - (x^2)}} \right]$$ Derivative of the arc function

$$A = 2\pi \int_x^R F(x)\sqrt{1 + f(x)^2}\,dx$$ Area formed by 'S', starting from x and going to 'R'

$$A = 2\pi \int_{R\cos(a)}^R R\,dx$$ Simplify and replace 'x' with 'R' times cos(a)

While Equation 1 is given in the IrDA standard documentation, the above derivation is not. This form is important because the "half-angle", as shown by angle 'a' in Figure 1, is usually given by the emitter and detector manufacturers.

EQUATION 1: AREA FUNCTION GIVEN ANGLE 'a'

$$A = 2\pi R^2(1 - \cos(a))$$

The number of steradians in a given solid angle can be determined by dividing the area on the surface of the sphere lying within the intersection of the solid angle by the square of the radius of the sphere, as indicated in Equation 2.

EQUATION 2: STERADIAN AS A FUNCTION OF AREA AND RADIUS OF A SPHERE

$$Sr = \frac{A}{R^2}$$ Steradian definition

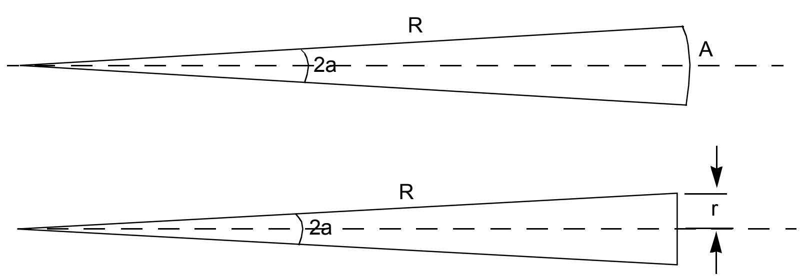
At relatively long distances from the emitter, the curved surface area, defined by 'A', can be replaced by the area of a flat circle, as indicated in Figure 3 and Equation 3.

EQUATION 3: STERADIAN APPROXIMATION

$$Sr = \frac{\pi r^2}{R^2}$$ use a relatively long distance from emitter

We now have the tools to calculate the area the emitted light of a point source (Light Emitting Diode) is spread over, at both short and long distances.

FIGURE 3: FLAT CIRCLE APPROXIMATES SEGMENT OF SPHERE



Let's consider a case where the radius of a sphere is 1 meter and a = 15° (the minimum half-angle for emitters and detectors, as defined by the IrDA Physical Layer specification). How is ±15° converted to steradians? To begin with, calculate the area of the sphere that is intersected by the solid angle:

$$R = 1\ meter \quad \text{Radius of the sphere}$$

$$a = \frac{(15)}{180}\pi \quad \text{Convert the angle to radians}$$

$$A = 2\pi R^2(1 - \cos(a))$$

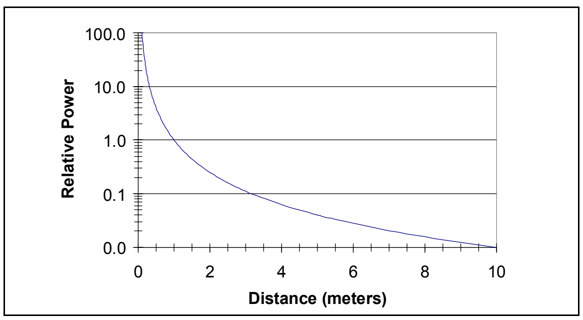
$$A = 0.214\ meters \quad \text{Projected area of solid angle}$$

Finally, from Equation 2, the number of steradians is calculated by dividing the area, A, by the square of the radius, R. Therefore, 0.214 steradians translates to an area of 0.214 m^2 when the radius is 1 meter and the half-angle is 15° (by definition, the number of steradians is equal to the projected area on a unit sphere).

Steradians and Light Energy

If the radius were increased to 2, ‘A’ would increase by a factor of 4 (while maintaining the same half-angle). This distance-square function of the area is the reason the available power drops as a function of the square of the distance. The *total* power projected on the larger area is the same, though the area that the power is distributed across increases. This relationship is illustrated in Figure 4.

FIGURE 4: POWER AS A FUNCTION OF DISTANCE



Other Units

Modern IR emitters used for data communication are usually specified in mW/Sr. Another unit sometimes used is millicandela (mcd). Visible LEDs are commonly specified in mcd. One candela is also the same as one Lumen/Sr. The candela is a unit of luminous flux, defined by the General Conference of Weights and Measures (CGPM).

The definition of the candela is the luminous intensity, in a given direction, from a source that emits a specified monochromatic radiation. There are actually two parts to this definition, the *intensity* and the *wavelength*.

The radiant *intensity* of the source is specified at 1/683 W/Sr, or 1.46 mW/Sr. One mcd is, therefore, equal to 1.46E-3 mW/Sr. However, it should be noted that the radiant intensity of an emitter is dependent on the angle at which the light source is measured. This is discussed in more detail in the next section.

The *frequency* of the source is specified at 540e12 Hz, or a wavelength of 555 nm (this light is green in color and is very close to the peak sensitivity of the human eye). When a calibrated photo detector is used, the calibration is established at a narrow wavelength. This part of the definition indicates the wavelength of this calibration, but the definition may be used at any wavelength.

THE IR LIGHT EMITTER

There are many off-the-shelf, commercially available, IR LED emitters that can be used for a discrete infrared transceiver circuit design. It should be mentioned here that there are also a number of integrated transceivers that the designer can choose as well. However, designing a discrete transceiver yourself may yield significant gains in distance, power consumption, lower cost or all the above.

In general, there are four characteristics of IR emitters that designers have to be wary of:

- Rise and Fall Time
- Emitter Wavelength
- Emitter Power
- Emitter Half-angle

The IrDA Physical Layer specification provides guidance for a given active output interface at various data rates, both in “Low-power” and “Standard” configurations. Table 1 summarizes the primary specifications in the low-power configuration (20 cm in distance) at data rates up to 115.2 kbps.

TABLE 1: IrDA STANDARD LOW-POWER ACTIVE OUTPUT SPECIFICATION

Specification	Min.	Max.	Units
Peak Wavelength	850	900	nM
Intensity in Angular Range (Emitter Power)	3.6	72	mW/Sr
Half Angle	15	30	Degrees
Rise and Fall Time	—	600	nsec

Table 2 summarizes the primary specifications in the standard configuration (up to 1 meter in distance) at data rates up to 115.2 kbps.

TABLE 2: IrDA STANDARD ACTIVE OUTPUT SPECIFICATION

Specification	Min.	Max.	Units
Peak Wavelength	850	900	nM
Intensity in Angular Range (Emitter Power)	40	500	mW/Sr
Half Angle	15	30	Degrees
Rise and Fall Time	—	600	nsec

The designer may desire to modify these requirements based on the particulars of the application. For example, an application may be required to communicate over a greater distance than 1 meter. In this case, the required light intensity may need to be greater than the stated maximum intensity specified by the IrDA specification.

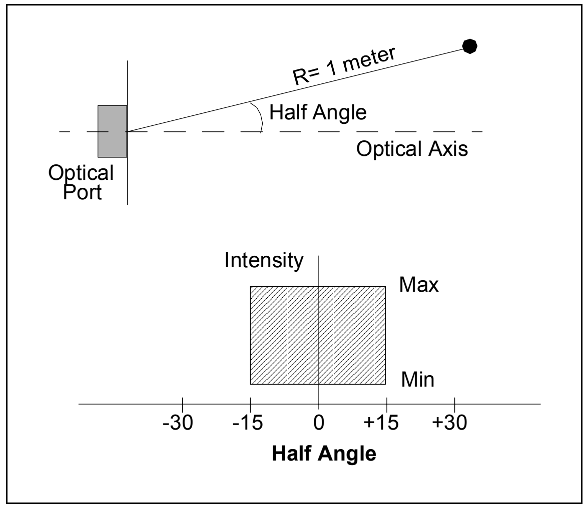
The first, and most important, emitter specification is its switching speed, expressed as t_{on}/t_{off} in most data sheets. Although the IrDA standard allows t_{on} to take up to 600 ns, the authors have had more consistent results when t_{on} is not more than 100 ns. Emitters used for TV Remote (TVR) applications may have t_{on}/t_{off} times of several microseconds and are not suitable for IrDA applications. If t_{on} or t_{off} are not specified, it can be measured with an oscilloscope. The rise (or fall) time of the current will equal the rise (or fall) time of the light pulse.

The emitter wavelength is usually given as the wavelength that the peak emission, or intensity, occurs. The intensity of larger or smaller wavelengths will fall off as they get farther away from the peak. The IrDA specification defines a range of light frequency that a compatible system will operate at. IR emitters that fall just outside this range may also be considered, but the relative radiant power at the desired wavelength (between 850 to 900 nm) may need to be determined.

To select an appropriate IR Light Emitting Diode (LED), the designer must also consider the emitter power in terms of the light to be made available at a desired distance of communication, as well as the amount of current required to generate the desired light energy.

The amount of light energy, or intensity, is given in mW/Sr and is measured at 1 meter. It is also specified that this intensity will be present over the angular range of the receiver, which is given as 15° (min). This is important because the light from a typical LED is not evenly distributed. Figure 5 illustrates the relationship of angular angle to the emitting diode, and light intensity requirements of the IrDA standard at the minimum angular range of 15°.

FIGURE 5: OPTICAL PORT ANGLE MEASUREMENT



Analysis of an IR LED

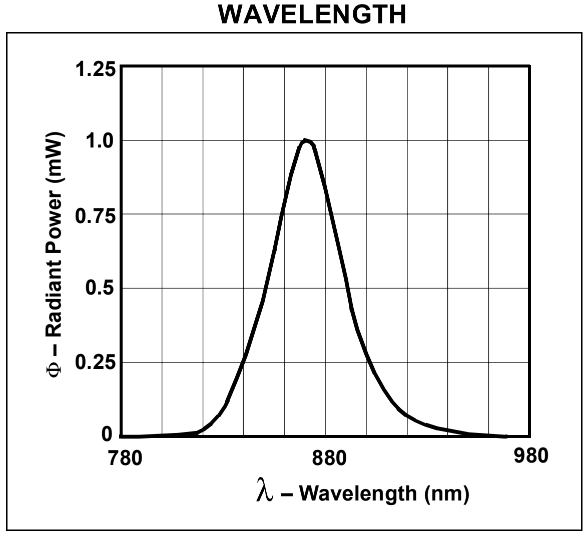
Let us now consider an actual IR LED, the Vishay™ TSHF5400, to determine if it will meet these guidelines.

EXAMPLE 1: IR LED ANALYSIS

Emitter Type:	TSHF5400
Emitter Pulse Current:	300 ma
Angular Displacement:	0 Degrees
Link Distance:	1 m

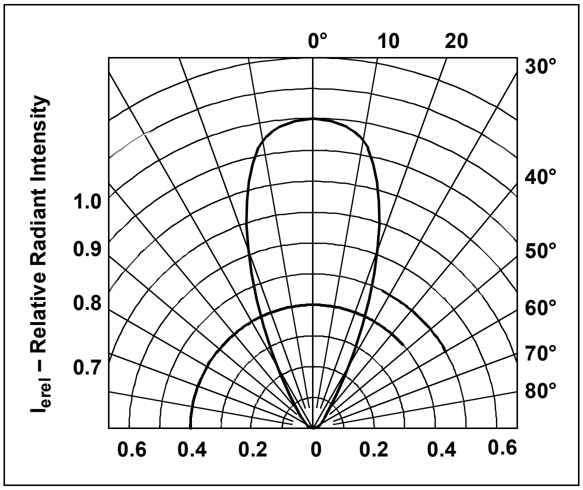
The peak wavelength for this LED is 870 nm. Figure 6 shows a graph of the Radiant Power (mW) versus Wavelength (nm).

FIGURE 6: RADIANT POWER VS. WAVELENGTH



As previously mentioned, the amount of light from a light-emitting diode is not evenly distributed. Figure 7 is a graph of the Relative Radiant Intensity (i.e., Emitted Power) versus Angular Displacement for a Vishay TSHF5400 IR emitter.

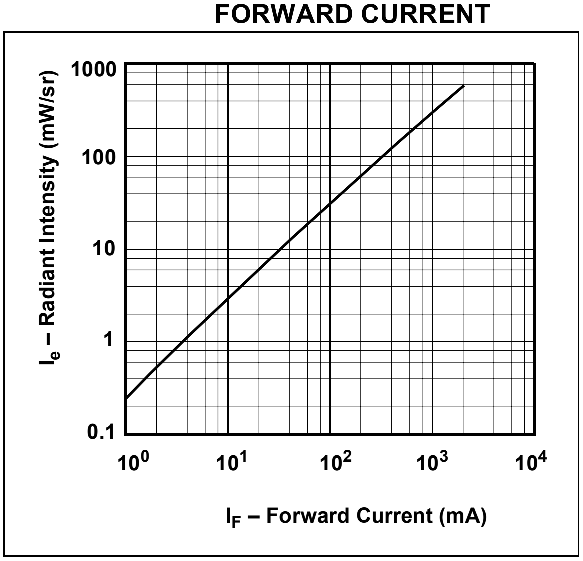
FIGURE 7: NORMALIZED INTENSITY VS. ANGULAR DISPLACEMENT



Since this graph is "normalized" (the relative strength is shown versus the angle at which the light is measured), the rated output is only available at an angle of 0°. At an angle of 15°, the output drops to 80% of the rated output.

Finally, the graph illustrated in Figure 8 indicates the radiant intensity that can be expected when the LED is provided a forward current.

FIGURE 8: RADIANT INTENSITY VS. FORWARD CURRENT



For this example, let's say the LED driver in the application can provide an emitter current pulse of 300 mA. So how much light can be expected?

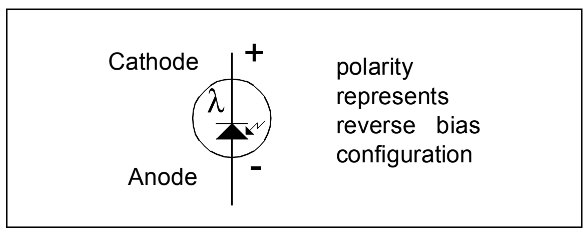
The graph shown in Figure 8 indicates that, for a current of 300 mA, the light intensity is about 100 mW/Sr., with a relative radiant intensity of 80% at an angle of 15° (indicated in Figure 7). Therefore, a minimum intensity of 80 mW/Sr can be expected at a distance of 1 meter within the angular range of 15° (the minimum half-angle specified by the IrDA standard).

> **Note:** The IR emitter and detectors may be on a Printed Circuit Board (PCB) that is within an enclosure behind a plastic window. An additional loss may be incurred, depending on the type of material and its thickness. For this example, no loss is assumed. In practice, most types of plastic with a thickness of 1.5 mm will lose about 10%. The same thickness of glass will lose 2-3%.

THE IR LIGHT DETECTOR

The most common device used for detecting light energy in the IrDA standard data stream is a photodiode. Integrated IrDA standard transceivers use a photodiode as the receiver, while TVR applications commonly use a photo transistor. Photo transistors are not typically used in IrDA standard-compatible systems because of their slow speed. Photo transistors typically have t_{on}/t_{off} of 2 µs or more. A photo transistor may be used, however, if the data rate is limited to 9.6 kb with a pulse width of 19.5 µs. Figure 9 shows a common symbol for a photodiode.

FIGURE 9: PHOTODIODE



A photodiode is similar in many ways to a standard diode, with the exception of its packaging. A photodiode is packaged in such a way as to allow light to strike the PN junction. In infrared applications, it is common practice to apply a reverse bias to the device. Refer to Figure 12 for a characteristic curve of a reverse biased photodiode. There will be a reverse current that will vary with the light level. Like all diodes, there is an intrinsic capacitance that varies with the reverse bias voltage. This capacitance is an important factor in speed.

Another operating mode occurs near the device breakdown voltage. Near breakdown, the velocity of minority charge carriers crossing the junction is increased. These high-energy charge carriers strike atoms in the depletion region, causing a large number of charge carriers to be knocked out of these atoms, causing a chain reaction of avalanche current. Light striking the junction will enhance this effect. Operating in the avalanche mode involves applying a constant current power supply to the reverse biased photodiode. This power supply must have a sufficiently high voltage to reach the device breakdown voltage. When light strikes the junction, the voltage needed by the power supply to maintain the constant current will be reduced. This method offers both high-speed and very high sensitivity. The disadvantage is both high cost and high-power consumption. This method is seldom used outside of military applications.

Link Distance

To select an appropriate IR photo-detect diode, the designer must keep in mind the distance of communication, the amount of light that may be expected at that distance and the current that will be generated by the photodiode given a certain amount of light energy.

The IrDA Physical Layer specification provides guidance for a given active-input interface at various data rates, in low-power and standard configurations. Table 3 summarizes the primary specifications in the low-power configuration (up to 20 cm in distance) at data rates up to 115.2 kb/s.

TABLE 3: IrDA STANDARD LOW POWER ACTIVE INPUT SPECIFICATION

Specification	Min.	Max.	Units
Irradiance in Angular Range	9	$5x10^5$	$\mu W/cm^2$
Half Angle	15	—	Degrees
Receiver Latency	—	0.5	msec

Table 4 summarizes the primary specifications in the standard configuration (up to 1 m in distance) at data rates up to 115.2 kb/s.

TABLE 4: IrDA STANDARD ACTIVE-INPUT SPECIFICATION

Specification	Min.	Max.	Units
Irradiance in Angular Range	4	$5x10^5$	$\mu W/cm^2$
Half Angle	15	—	Degrees
Receiver Latency	—	10	msec

As with the IR LED, the designer may wish to modify these design guidelines based on the particulars of the application.

The amount of light energy, or irradiance, that is present at the active-input interface is typically given in $\mu W/cm^2$. This is a convenient scale of light flux. Light energy given in mW/Sr can be converted to $\mu W/cm^2$ as follows. Recall from Equation 2 that:

$$Sr = \frac{A}{R^2}$$

To convert Sr to cm^2, the distance must be known. In this example, R = 1 meter. The area of the circle of interest can be set to one square centimeter (0.0001 m^2). So, at a distance of 1 meter, the area of 1 steradian is equal to 1 square meter (or 10,000 cm^2). It follows that 40 mW/Sr is equal to 4 $\mu W/cm^2$, the minimum irradiance requirement of the IrDA standard configuration active input.

It is also specified that this irradiance must be present over a minimum angular range of the receiver, which is given as 15°.

It is interesting to note that at a distance of 2 feet, or 0.6 meters, an IrDA standard-compliant emitter will provide 2.8X the light intensity that is available at 1 meter, based on the distance-squared function stated in Equation 2 and illustrated in Figure 4.

The latency of the input interface must be less than 10 msec.

Analysis of a Photo-Detect Diode

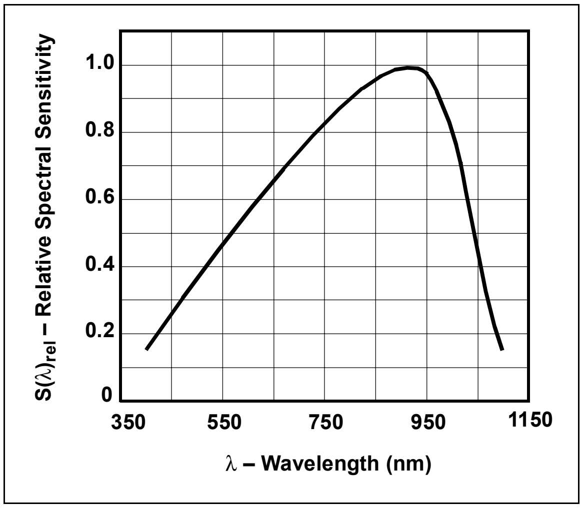
Let us now consider an actual IR photo-detect diode, the Vishay BPV10, to determine if it will meet these guidelines.

EXAMPLE 2: PHOTO DIODE ANALYSIS

Receiver Type:	BPV10
Angular Displacement:	15 Degrees
Link Distance:	1 m

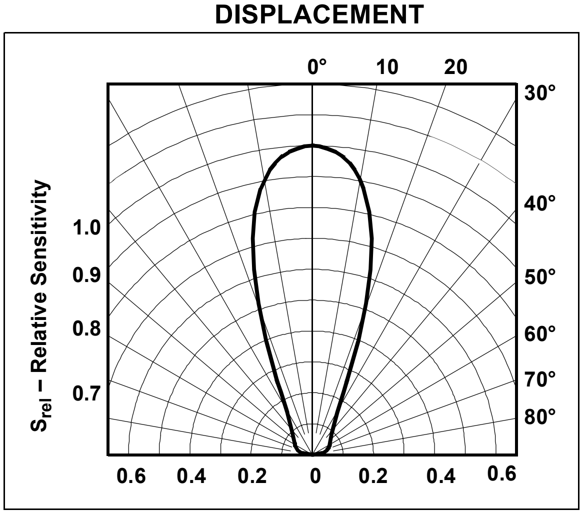
The peak wavelength for this diode is 950 nm. Figure 10 shows a graph of the Relative Spectral Sensitivity versus Wavelength (nm).

FIGURE 10: SENSITIVITY VS. WAVELENGTH



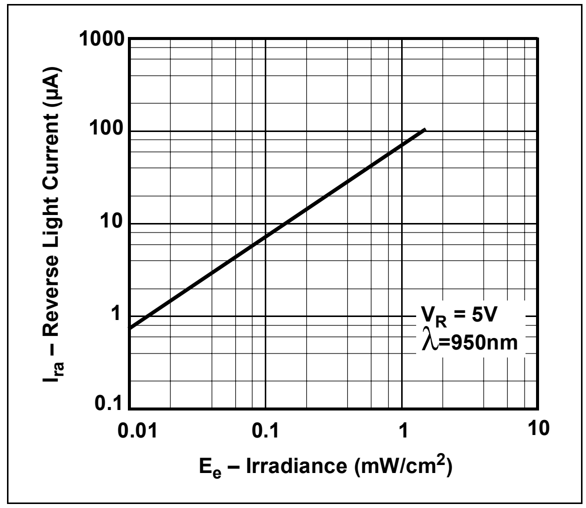
The light sensitivity of a photo-detect diode varies according to the angle of the light source. Figure 11 is a graph of the Relative Radiant Sensitivity versus Angular Displacement for a Vishay BPV10 photo-detect diode. At a half-angle of 15°, a relative sensitivity of 75% can be expected.

FIGURE 11: NORMALIZED SENSITIVITY VS. ANGULAR DISPLACEMENT



Finally, the graph illustrated in Figure 12 indicates the reverse current that can be expected when the Photodiode is subjected to a light irradiance.

FIGURE 12: IRRADIANCE VS. CURRENT



The reverse light current goes up with increasing levels of irradiance, as expected. The reverse current is also roughly linear to the irradiance. That is, if the light irradiance is reduced by a factor of 10, the reverse light current is also reduced by a factor of 10. The irradiance is scaled in mW/cm^2. Extrapolating the graph in Figure 12 indicates that a light pulse of 0.004 mW/cm^2 (40 mW/Sr) will generate a reverse current level around 0.33 µA. Noting that the relative sensitivity at a half-angle of 15° is 75% per Figure 11, a current pulse of about 0.25 µA could be expected at this half-angle.

Recall that light energy (intensity) increases exponentially with respect to distance (Figure 4). At a distance of 2 feet, or 0.6 meters, the amount of energy and, therefore, the reverse current, is roughly 2.8X the energy present at 1 meter. In this example, a current pulse of 0.7 µA could be expected at 2 feet at a half-angle of 15°. If larger distances are required, a photo-detect diode with higher sensitivity may be required. Another alternative is to use two or more diodes in parallel to generate more current at low light energies.

In general, the cost of the photo-detect diode will increase with increased performance. A diode with a larger photo-sensitive area can be selected to provide a higher current output, but this will increase the overall cost of the discrete transceiver circuit. The distance requirement of the application should be clearly defined at the outset of the design, allowing the system designer to provide an adequate and cost-effective solution.

INCREASING THE LINK DISTANCE

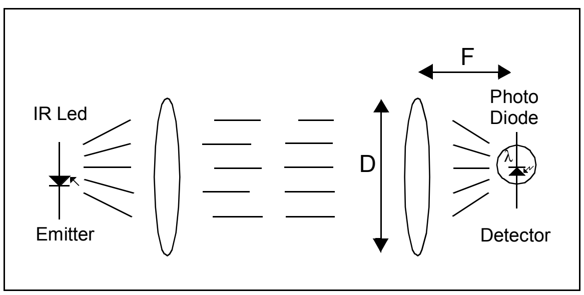
Finally, more than one meter may be required for IR communication in some applications, even though the physical layer of the IrDA standard configuration is built around this distance. Let's take an example where an application needs to communicate with a standard device, like a Palm™ PDA, at an extended distance. Since the power emitted by the Palm IR driver is fixed, one approach would be to ensure that the sensitivity of the receiver is sufficient to support the available light intensity. Increasing this sensitivity by a factor of 4 would only double the distance to 2 meters. The receiver cost and complexity will therefore increase much faster than the increase in distance. As mentioned in the previous section, two or more photo-detect diodes can be connected in parallel to achieve a higher current output. Such an increase in sensitivity takes care of one-half of the link, but data must be sent back to the Palm PDA as well.

Increasing the emitter power by a factor of 4 would also increase the link distance to 2 meters. This approach has limited potential because the emitter power must be limited for eye safety reasons. The pupil of the human eye will not react to IR light and the instinct to look away is not triggered. A single-point IR source of greater than 200 mW/Sr at 1 meter should be avoided for this reason.

Multiple emitters can be used to circumvent this problem. 4 meter IrDA standard links have been designed by using 16 IrDA standard-compliant emitters. Of course, using such a large number of emitters has obvious trade-offs in cost, power and complexity.

Another approach involves using lenses. Figure 13 shows a possible combination of lenses. Lenses have no moving parts and may be fabricated from inexpensive plastics. Plastic lenses are not common for visual applications due to the fact that loss and spectral distortion occurances are higher than with glass. With infrared applications, we're only interested in a single wavelength of light so spectral distortion is not a factor. Loss is also not a factor because multiple lenses will not be used.

FIGURE 13: USING A LENS TO INCREASE DISTANCE



In practice, it's more common to be compatible with a standard device (e.g., Palm PDA), so one lens on the photo-diode (detector) side will suffice. If compatibility with a standard device is not an issue, links on the order of tens of meters can easily be achieved by implementing lenses on both sides.

An application using Optical Lenses

What lens specification would be needed to establish an IR link at a distance of 5 meters? Assume an emitter power of 200 mW/Sr, a minimum threshold irradiance requirement of 0.02 mW/cm^2 and a half-power angle of ±15°.

The two specifications of interest in this lens are the focal length and diameter. The amount of energy gathered by the lens is a function of the diameter. As we calculated earlier, an area of 1 cm^2 at a distance of 1 meter is a solid angle of 1 x 10^{-4} Sr. The calculation we performed earlier is as follows:

$$200\frac{mW}{Sr} \times 10^{-4}\frac{Sr}{cm^2} = 0.02\frac{mW}{cm^2}$$

To keep the same level of light flux, we need to keep the same solid angle (1 x 10^{-4} Sr) and determine the projected area at 5 meters.

EXAMPLE 3: CALCULATING THE RADIUS OF THE LENS (r)

$$Sr = \frac{\pi r^2}{R^2}$$

We know the angle and R is given as 5 meters. The radius of the lens is r

$$R = 5\ m \qquad Sr = 1 \times 10^{-4}$$

$$r = \sqrt{\frac{S_r \cdot R^2}{\pi}} \qquad r = 0.028\ meters$$

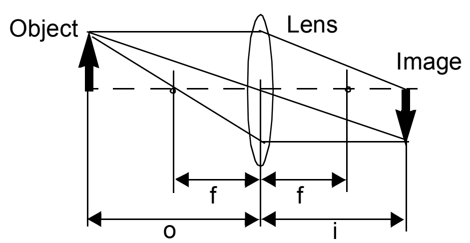
Rearrange and solve for r

The radius of the lens must therefore be 2.8 cm (a diameter of 5.6 cm) in order to capture the same level of light flux that was available within a 1 cm^2 area at a distance of 1 meter.

Next, we need to determine the distance between the lens and the photodiode. The Thin Lens equation, in Gaussian form, is given in Equation 4, where 'o' is the object distance, 'f' is the focal distance and 'i' is the image distance.

EQUATION 4: THIN LENS EQUATION

$$\frac{1}{o} + \frac{1}{f} = \frac{1}{i}$$



For most applications, 1/object distance is approximately zero. Therefore, the focal length and diameter are the two specifications needed to select the lens.

There are several factors to consider when specifying the focal length, including ease of packaging, depth of field and the amount of energy to capture. A longer focal length will make the lens easier to focus (larger depth of field) but will make the application physically larger.

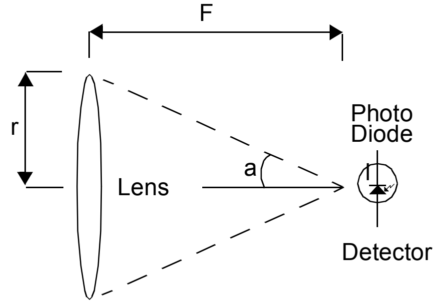
Let's assume that the half-power angle, which is also the angle of half-sensitivity, will subtend the outer edge of the lens. In this case, the lens radius 'r' is 2.8 cm and the angle 'a' is given as 15°. The focal length calculation is shown in Equation 5.

EQUATION 5: FOCAL LENGTH CALCULATION

$$tan(a) = \frac{r}{F}$$

$$F = \frac{2.8}{\left(tan\left(\frac{\pi}{12}\right)\right)} \qquad F = 10.45$$

The focal length is 10.5 cm. An Anchor Optical AX76364 is a good fit, with a diameter of 5.8 cm and a focal length of 10 cm.



CONCLUSION

Whether designing to the IrDA standard or developing a custom interface, the fundamentals of the infrared physical layer are straightforward, since the behavior of IR is easy to predict.

The system designer can use an integrated transceiver or select low-cost, off-the-shelf components to implement an effective IR port, once the Link Budget and application requirements are understood.

REFERENCES

1. Infrared Data Association Serial Infrared Physical Layer Specification, Version 1.4, May, 2001.
2. "High Speed IR Emitting Diode in ϕ 5 mm (T-1¾) Package", TSHF5400 Data Sheet, Vishay Semiconductors, 1999.
3. "Silicon PIN Photodiode", BPV10 Data Sheet, Vishay Semiconductors, 1999.

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