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INTELLIGENT OPTO SENSOR **Number 36**

DESIGNER'S

NOTEBOOK

Proximity Detection and Optical Lenses

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Overview

The TAOS TSL277x, TSL267x and TCS377x series of proximity detectors, used in conjunction with an external LED(s), provide a robust and cost-effective means of sensing proximity. Maximum sensing distance depends on various factors such as target size, reflectivity, LED power, cover material above the detector and LED devices, LED half power angle, and the number of LEDs used. Using a lens above the detector adds complexity and cost; however a lens can significantly extend the proximity detection distance.

All TAOS proximity detectors provide an internal switching transistor capable of sinking up to approximately 100mA of current to power the external LED. Multiple LEDs can be driven by the same transistor if the LEDs are connected in series. This may require a higher V_{LED} voltage (i.e. $V_{LED} > V_{dd}$) in order to overcome the forward voltage drop of the multiple LEDs. Although the proximity detector can be used with visible LEDs, it is typically used with IR (Infra-Red) LEDs; such as, the Osram SFH4650 or other high power LEDs.

In addition, the proximity detector could drive an external switching transistor allowing it to drive LED(s) to much higher IR power levels. In this designer's notebook, the main focus is on optical considerations such as the use of a lens in conjunction with the proximity detector but it will also discuss the effect of system apertures on the angular response of the proximity system and the choice of LEDs with various angular beam characteristics.

Choosing LED(s)

LEDs are available in a wide range of power levels and half-power beam angles. An optically focused LED is recommended to extend the maximum proximity detection distance, and the focusing is typically done with either a lens structure or a curved reflector. For example, Osram SFH series of LEDs are available with half power beam angles of 5, 10, 12, 15 and 20°. Vishay LEDs are also available in a variety of half power beam angles. Smaller beam widths provide higher radiance levels on or near the LED beam axis. Radiance is measured in units of watts per steradian.

The LED beam width is selected based on the proximity sensor's angular field of view and the target size. For instance, when considering an infinitely large target, the proximity sensor's response drops off as the function $1/d^2$ where d is the distance between the target and sensor. However, when considering a small target with a wide angle LED beam, the LED IR light may well overspill the target. This especially true if a target is off of the axis of the LED. So as the target distance increases from the sensor to the point where LED illumination overspills the target, the proximity response will eventually fall off as $1/d^4$, not as $1/d^2$. For this reason, LEDs with smaller half power angles can enhance maximum proximity detection distance by trading off the sensor's usable field of view.

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Figure 1 shows the Vishay (part number VSMG2000X01 and VSMG2020X01) LED specifications for Relative Radiant Intensity with half power angle of ±12°.

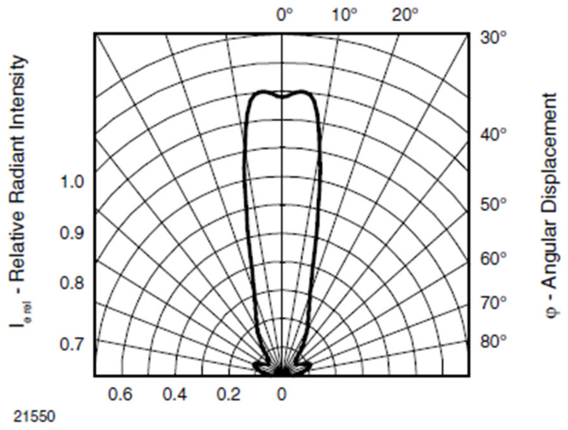

Figure 1: Vishay LED Angular Radiation Pattern

Using Lenses with the Proximity Device

In addition to selecting LEDs with a narrow beam angle, there are benefits to using a lens over the detector to narrow the detector's field of view. Narrowing the detector's field of view, increases the amount of light focused at the detector's active area, thereby increasing proximity detection distances. Since some proximity detectors are also capable of doing Ambient Light Sensing (ALS), using a lens to increase the proximity distance will also narrow the field of view for ALS. To understand these applications and the principles behind the use of optics, basic optics principles of both no lens systems and lens systems will be reviewed.

No Lens System

The proximity detector has an effective light gathering area equal to the device's active area (A) which for the TSL2771 is A = 0.467mm x 0.467mm = 0.218mm^2. In addition, the device has a cosine angular response; such that, the device's IR light response is proportional to cos(θ) where θ is the angle of the incident light. If the proximity detector is placed behind an aperture (often done to help disguise the part from the customer), the angular extent of the aperture further constrains the angular response of the device. Figure 2 shows an example of a sensor with no lens (i.e. cosine response) and with circular aperture limiting angular response to ± 40°.

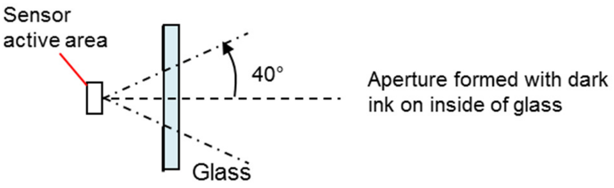

Figure 2: Sensor with No Lens

For example if the aperture is much larger than the active area, then the setup shown in Figure 2 will have an angular response approximated by:

$$R(\theta) \cong \begin{cases} kA \cdot \cos\theta \text{ , } |\theta| \leq 40^\circ \\ 0 \text{ , } \quad |\theta| > 40^\circ \end{cases} \qquad \text{Equation (1): Angular Response}$$

where k is a constant of proportionality, and A=0.218mm^2 for TSL2771.

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Lens System

Consider an optical system where a lens is added to increase the effective light gathered at the active area, so to appear much larger than the 0.218mm^2 active area. Figure 3 shows an Optical lens system for calculating viewing angle using a lens. The lens system of Figure 3 can be analyzed using the "imaging equation":

$$1/d_1 + 1/d_2 = 1/f \qquad \text{Equation (2): Imaging Equation}$$

where f is the focal length of the lens. Assuming that D is much larger than the active area extent (0.467mm), approximations can be accurately used to simplify the analysis.

The "back distance" (d_1) between the lens and the detector should be chosen to be LESS THAN the focal length of the lens. With the active area of the device representing the "object" in this imaging system, a "virtual image" of the active area appears at the location labeled "I" in Figure 3. I.e. the image distance d_2 is "negative", indicating the formation of a virtual image, rather than a real image. (If the back distance d_1 had been chosen to be GREATER than the focal length, then d_2 would have been positive, and there would be a REAL image). This result is then used to calculate the effective "viewing angle" of the detector placed behind the lens. From the Equation 2, $d_2 = f \cdot d_1/(d_1 - f)$, and since d_1 is less than f, d_2 is negative (i.e. a virtual image that is located on the same side of the lens as is the "object"). D is the diameter of the lens, and using some trigonometry find the "viewing angle", α, to be:

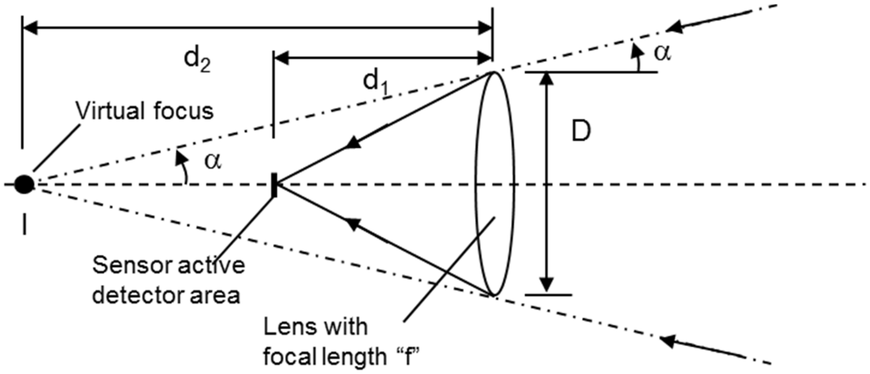

Figure 3: Calculating the Viewing Angle

$$\alpha = \arctan\left(\frac{D/2}{d_2}\right), \text{ where } d_2 = \frac{f \cdot d_1}{d_1 - f} , \qquad \text{Equation (3a): Viewing Angle}$$

or in terms of d_1 and f

$$\alpha = \arctan\left[\frac{D}{2f}(1\text{-}f/d_1)\right] \text{(viewing angle of the detector).} \qquad \text{Equation (3b): Viewing Angle}$$

The highest optical gain is when d_1 = f, and the viewing angle is 0°. This is like putting the device at the back focal point of the lens which gives maximum intensity, but requires that the proximity target be on-axis or very close to on-axis in order to be seen by the proximity system.

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For example if the sun is the light source, then the sun is virtually infinitely far away, i.e. $d_2 = +\infty$, and from Equation 2, $1/d_1 = 1/f - 1/d_2 = 1/f - 1/\infty = 1/f$, or $d_1 = f$, in which case the sun would be imaged onto the detector and the image would be in focus.

Optical gain is defined as the ratio of the light intensity incident on the detector to the light intensity incident at the front of the lens. The circular aperture of the lens (shown in blue in Figure. 4) will project to a smaller circular area (shown in green in Figure 4) in the plane of the detector.

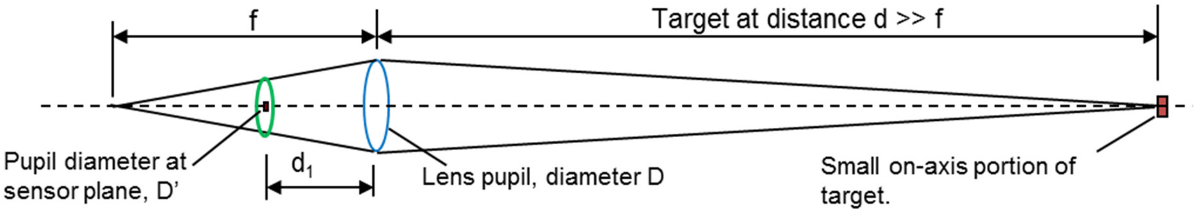

Figure 4: Calculating the Optical Gain

Assuming that the target is far away (i.e. at distance d >> f), then a small on-axis portion of the target images to the back focal plane of the lens at a distance f. Since virtually all the light incident on the lens passes through the lens to the back image point, the intensity, being power per unit area, should increase inversely with the area of the circular pupils.

Calling the pupil diameter at the detector plane D', and the lens diameter D, then the area of the circular pupils goes as $\pi D^2/4$ (proportional to D^2) such that the optical gain is given by $G = (D/D')^2$. Using the principle of "similar triangles" it is evident from Figure 4 that $D'/D = (f-d_1)/f = 1-d_1/f$, or that the optical gain is given by:

$$G = (D/D')^2 = \left(\frac{1}{1-d_1/f}\right)^2 = \left(\frac{f}{f-d_1}\right)^2$$ Equation (4): Optical Gain

So for example, choosing $d_1 = f/2$ gives an optical gain of four. For a sufficiently large on-axis target the proximity response will be $1/d^2$, such that an optical gain of four should increase the maximum proximity distance by a factor of two.

The smaller the viewing angle, the higher the optical gain. In general the optical gain will be inversely proportional to the square of the viewing angle, i.e. $G \propto (1/\alpha)^2$, yet the viewing angle should be large enough to fully encompass the angular emission pattern of the LED(s) as it appears on the target.

Although LEDs are often parameterized by a "half power angle" (the angle where the intensity of the LED drops to ½ of its on-axis maximum value) there is still appreciable LED light power outside of this angle. Thus it is prudent to make the detector viewing angle somewhat larger than the ½ power angle of the LED.

Inspection of Equation 4 shows that there are two parameters that control optical gain, f and d_1. There is no "unique" solution to achieving a particular optical gain. Ultimately what matters is the ratio of f (the lens focal length) and d_1 (the back distance between the lens and the detector). Also important is the lens diameter D, in that for a given setback distance d_1 from lens to the detector, it also impacts the maximum viewing angle per Equation 3. The setback distance is generally constrained in many designs (e.g. implementing the detector in a thin display panel or in a thin cell phone package). In this case the focal length of the lens may have to be correspondingly smaller as d_1 is reduced. The ratio of f/D is known as the "F#" or "F number" of the lens. Smaller *f* numbers correspond to "stronger" lenses having higher "curvature".

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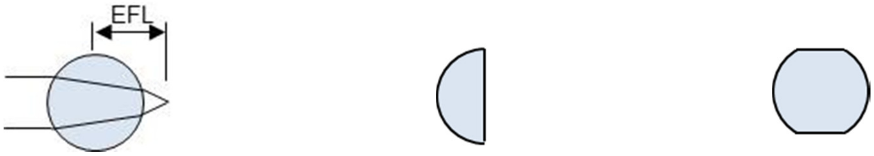
Examples of small strong lenses used in proximity applications include the ball lens, the half-ball lens and the drum lens. These lens types are available in many sizes and focal lengths from companies such as Edmund Optics.



a.) Ball Lens b.) Half Ball Lens c.) Drum Lens

Figure 5: Strong Lenses

A good choice for a lens is a small half-ball lens (diameter determined by system constraints), where the back distance (d_1) can be adjusted as desired (i.e. a tradeoff between viewing angle and optical gain) with viewing angle given by Equation 3 and optical gain given by Equation 4. For the ball lens or the drum lens of radius R, as shown in Figure 5a, the EFL or "Effective Focal Length" is given by:

$$EFL = \frac{nD}{4(n-1)}$$

Equation (5): Effective Focal Length

where D is the ball diameter, and n is the refractive index (n ~ 1.5 for N-BK-7 glass).

Other Considerations

Several characteristic "regimes" are shown in Figure 6, which shows the output of a simulation using an IR LED with a half power angle of 25°. This simulation assumed a 10mm distance between the IR LED and the detector, and employed a 100m x 125mm sized target. At very close distances (the beginning "near field regime") the portion of the target that is illuminated by the LED is not in the field of view of the detector so there is no proximity response. As the object distance increases, the illuminated target portion encroaches into the field of view of the detector and the signal increases, reaching a maximum beyond where the signal then drops off. Initially all of the LED light reflects from the target and the signal drops off as $1/d^2$. At larger distances the LED light begins to overspill the target and eventually reach the $1/d^4$ regime.

Figure 6 shows the simulation of response vs. distance (not using lens). Note transition from -20 to -40dB/decade as target gets far enough away that LED illumination overspills the target area.

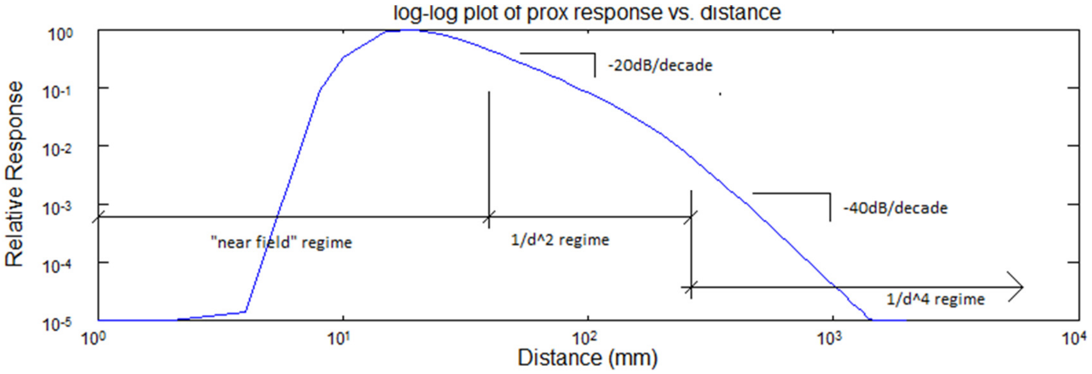


Figure 6: Simulation of Response vs. Distance

The important result here is that for long distance proximity, it is important to ensure that the target is large enough so that the LED illumination does not overspill the target. This condition can be met by using a LED with a "tighter" beam angle. If using a 200mm x 200mm target with a maximum proximity distance of 800mm, then this corresponds to an angle of: arctan[(200mm/2)/800mm] = 7.1° In this case, choose an LED with a half power beam angle of 5°. It is also important that the detector's field

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of view fully encompass the LED illumination area on the target. If it is critical to detect objects that are very close to the proximity sensor, then decrease the distance between the detector and the LED. The risk in making this distance too small is that it will tend to increase the optical crosstalk between the LED and detector where the system is placed behind a cover glass. Optical crosstalk is discussed in more detail in other applications notes.

Conclusion

The TAOS proximity detectors, used with an external IR LED, provides a very high performance optical proximity detection system in a compact and low cost package. This simple configuration is capable of doing robust proximity detection out to reasonably large distances. Detection distances can be extended by using additional LEDs or lenses. The simplest solution is to wire several LEDs in series and using the built in LDR pin of the detector to sink the current (using a sufficiently high voltage to drive the series string of LEDs). Additional proximity detection distance can be gained by using an external P-Channel FET to drive higher current LEDs. For large distances, it must be assured that the LED light does not overspill the target. This can be addressed by using LED’s that have narrowed half-power angle beams. For significantly larger proximity detection distances, use of a lens over the detector can significantly increase detection distance by providing optical gain for the detector, at the expense of decreasing the angular field of view of the proximity detection system.

This Designer’s Notebook Article has focused on the considerations and tradeoffs in designing lenses to improve optical performance and increase proximity detection distance. There are many other issues that must also be taken into account when designing an optical system. For additional information, please look for other Designer’s Notebooks for articles on designing optical systems such as DN34: Proximity Detection and Optical Crosstalk or DN35: Proximity Detection and IR Ink.

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