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INTELLIGENT OPTO SENSOR DESIGNER'S NOTEBOOK

Number 34



Proximity Detection IR LED and Optical Crosstalk

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Introduction

The TAOS proximity sensors provide a robust and cost-effective means for detecting the amount of light reflected from an object. However, this process is often complicated by introducing glass between the IR LED, which shines invisible light onto the target, and the sensor, which senses the very small amount of light reflected from the target to the sensor. The introduction of glass (or plastic) can create a path for optical crosstalk which is impacted by the air gap between the sensor/LED and glass, distance between the sensors and LED, enclosure where the sensor and LED reside and glass thickness. Careful systems design can control each of these factors and minimize their impact.

Crosstalk will also change depending upon the application. For long distance proximity, the highest possible power is needed which also increases the amount of crosstalk. For medium distance proximity such as used in a cell phone, the speed of the proximity detection is critical and must be implemented in a small area. For short distance proximity such as a push button or switch replacement, interaction between several adjacent parts becomes important to understand.

Types of IR LEDs

There are many types of IR LEDs that can be used in a proximity system. Some LEDs come without lenses in a flat clear package similar to our proximity sensor. These IR LEDs possess a very wide dispersion angle and will have the most crosstalk. These require a larger separation or very low power such as used in close distance proximity detection for optical switches.

The most recognized types of IR LEDs are the T-1 and T-1 $\frac{3}{4}$ with a lens built into the package. This provides a stronger focus, directing the light towards the target. These are useful where power must be maximized and size is not critical.

The Surface Mount (SMD) package with a lens is the most popular IR LED for cell phone applications because of the low profile. The clear package with the formed lens is the least expensive but creates more crosstalk since light comes out of the side of the package. The lowest profile and most powerful packages have a reflective bowl under the sensor instead of the lens above the sensor.

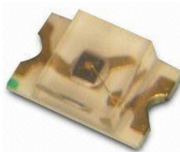


Figure 1A
No Lens



Figure 1B
T-1 or T-1 $\frac{3}{4}$ w/Lens



Figure 1C
SMD w/Lens



Figure 1D
SMD with Bowl

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Typical Proximity Detection System

Figure 2 depicts a typical proximity detection system behind glass. Several sets of rays that contribute to optical crosstalk are shown reflecting from various surfaces. While the sensor shown is the outline of the package, the active area is assumed to be a much smaller and can be approximated by a point in the middle of the package.

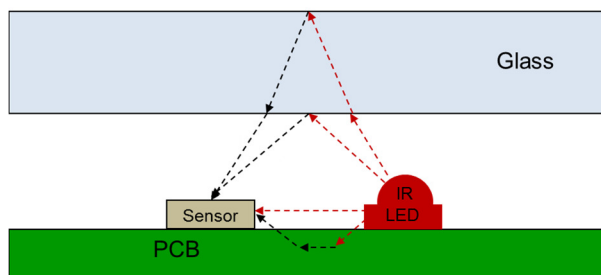


Figure 2: Typical Proximity Detection System behind Glass

Optical crosstalk paths include direct light propagation from the LED to the sensor, through the PCB from the LED to the sensor, from the bottom surface of the glass to the sensor and from the top of the glass to the sensor.

The direct light that travels from the IR LED towards the sensor is the first major issue that must be corrected. This light must be blocked by an optical barrier. Another significant source of optical crosstalk is scratches and contamination (e.g. makeup, skin oils, residue from perspiration) on the outside of the glass. For this reason, it is recommended that scratch-resistant materials be employed with outside surfaces that can be easily cleaned (e.g. tempered glass).

Optical Barrier

The first step in eliminating the crosstalk is to create a barrier between the IR LED and the sensor. Some IR LEDs are designed with an optical barrier as a part of the LED package but may depend upon the orientation of the LED. The barrier must consist of optically opaque material that contains a substance like carbon black that absorb unwanted IR energy. Figure 3 shows an example of an optical barrier that blocks light from the IR LED to the sensor.

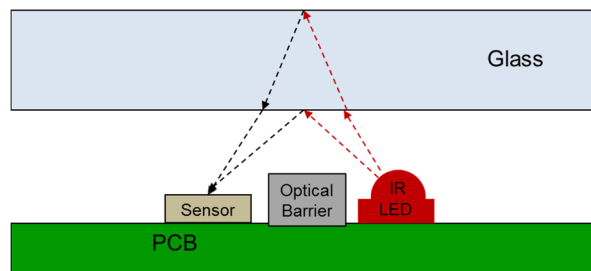


Figure 3: Optical Barrier

The next step is to eliminate possible crosstalk through the PCB. Having a metal plane on the top side of the PCB is a good start to keep light from penetrating the PCB. In addition mounting the sensor and LED on separate PCBs, or machining a groove or slot into the PCB will create an optical barrier penetrating down into the PCB and help to eliminate the crosstalk

In addition to the barrier between the LED and the sensor, stray light can bounce from any reflective surfaces (such as white plastic, shiny metal etc.) producing random light scattering. Stray light control is achieved by using black-plastic or metal housings that enclose the IR LED and sensor in IR opaque “compartments” with openings only facing the glass.

The next step is to eliminate crosstalk from the bottom of the glass. Although glass is “transparent”, about 4% of the incident light reflects from each surface of the glass due to a phenomenon called “Fresnel reflection”. An example is the glare of sunlight reflecting from a glass surface. Raising the height or increasing the width of the barrier will eliminate this crosstalk. If the barrier is made of a hard opaque plastic, there may need to be a gap between the glass and the sensor for mechanical reasons (e.g. ability to survive a drop test). If it is soft rubber, it may touch the glass as shown in Figure 4. In either case, the material must be opaque to IR light.



Figure 4: Optical Barrier – Eliminate Bottom Surface Reflection

While it is relatively simple to eliminate the bottom side crosstalk, eliminating the top surface crosstalk is more difficult and may require calculations to understand the requirements. The most obvious method is to increase the lateral separation between the sensor and the IR LED and fill the gap with the optical barrier. The second method is to minimize the air gap and the third is to minimize the glass thickness. A latter section will discuss the calculation related to the detailed design.

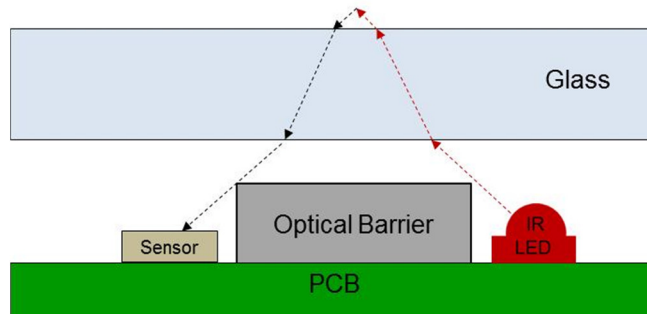


Figure 5: Optical Barrier – Wider Separation

If the separation cannot be increased, other options can be utilized. Increasing the barrier width and height can improve light blockage. If the barrier cannot touch the glass, dark IR light absorbent ink on the glass can be used to create a “shadow region” that effectively blocks crosstalk reflections from the outside surface of the glass as shown in Figure 6.

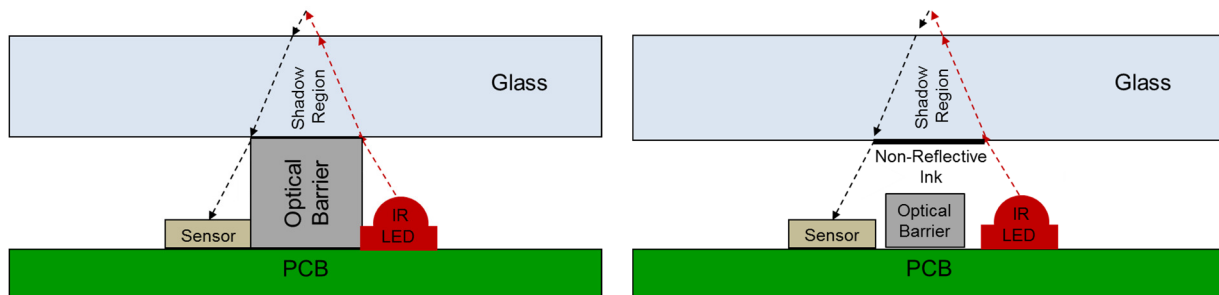


Figure 6: Optical Barrier – Blocking Reflection from Top Surface

The ink mask design must suppress crosstalk and not backscatter light emitted from the LED. The ink mask should have very good opacity to IR, and should have low reflectance to IR light.

Where the airgap between the sensor and the optical barrier cannot be kept very small ($<0.3\text{mm}$), an option is to utilize a “rubber boot” which is inexpensive to manufacture and easy to install. This soft rubber fills the gap between the sensor and LED as well as the gap between the sensor and the glass. The rubber boot then acts as the effective optical barrier. Figure 7 shows an example of a rubber boot.



Figure 7: Optical Barrier – Rubber Boot

When creating an optical barrier and an enclosure for the sensor and LED, make an aperture above the sensor and LED. This will restrict the light exiting from the LED and limit the light hitting the sensor. Please refer to DN13 Optical Window Design for details on the formulas for aperture design.

While the best implementation for a proximity sensor is behind perfectly clear glass, this is typically not desired by the cell phone manufacturer. Dark ink is often used to help “camouflage” the proximity sensor. This dark ink has minimal transmittance in the visible spectrum but is largely transparent to IR light. This dark ink can potentially contribute to crosstalk via optical scattering which is covered in DN35: Proximity Detection and IR Ink.

There are two types of ink that will be discussed. The term “black” ink will refer to any ink, film or other method used to conceal the electronics, and will typically not transmit any light. The term “dark” ink will be used to refer to translucent ink; glass with tinting, film or any other method used to partially hide the sensor while letting some of the light penetrate the dark ink and reach the sensor.

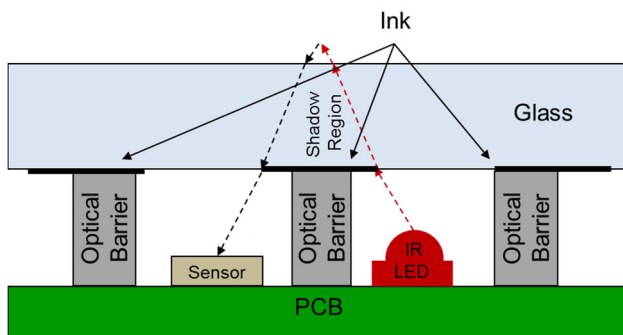


Figure 8a: Ink Aperture Side View

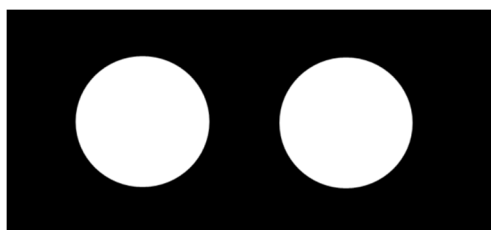


Figure 8b: Circular Ink Aperture – Top View



Figure 8c: “D” Shaped Ink Aperture – Top View

While a circular ink aperture may be adequate in some applications, others require a larger opening, such as when the IR LED has a wider beam angle or the sensor needs a wider angle of view to allow better ALS measurements. In these situations, a larger opening can be used, however the stripe width between the sensor and the IR LED must be maintained forming a “D” shaped aperture as shown in Figure 8c.

Mechanical tolerances must also be fully understood. Variation such as alignment from the glass to the sensor must be taken into account and the calculation for worst case design must be analyzed. Figure 9 shows the impact of a misalignment of the ink to the sensor shifting the critical point. This “critical point” defines a zone where objects beyond the critical point will have strong proximity response, and objects in front of the critical point will have very poor proximity response.

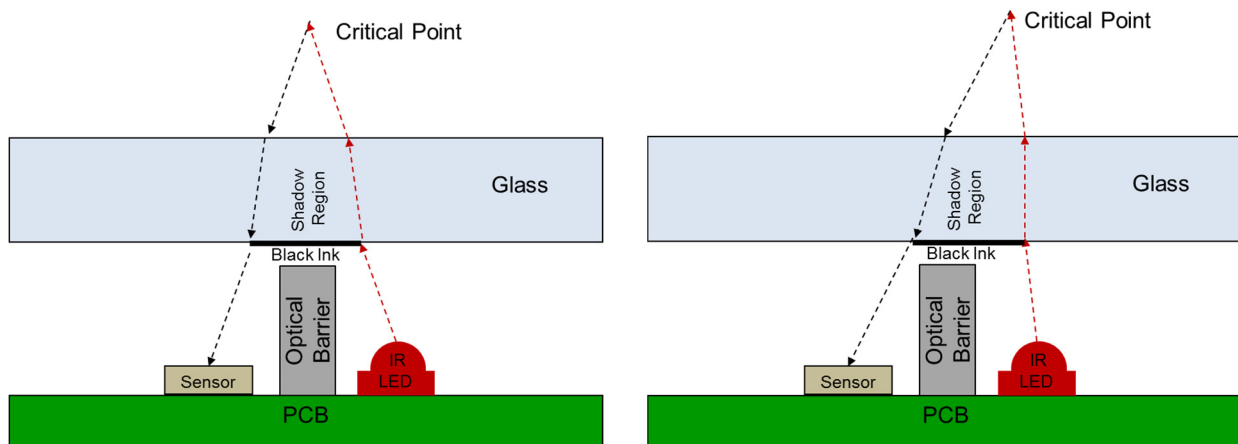


Figure 9: Mechanical Alignment

Use of Lenses to Improve Proximity Detection

One of the issues related to enclosing the IR LED in a cavity with a small opening is that a large amount of the IR light is absorbed by surrounding material and only a very small portion of the light is actually focused on the object to be detected. One method to improve this situation is to utilize an IR LED with a lens. For proximity detection the LED should have a relatively narrow “beam angle”. I.e. most LED’s are lensed to provide some degree of collimation, and the “half power angle” of the LED will usually be specified. The angular extent of the cone of light emitted from the LED can be made more distinctive by cutting off the cone using an aperture formed on the inside of the glass using opaque ink.

Similarly an aperture can be placed over the sensor detector to better define the “detection cone.” In addition, using a lens over the detector should also be considered to increase proximity sensing distance by providing optical gain and creating a more sharply defined “detection cone”. The intersection of the two cones results in a relatively well defined critical point.

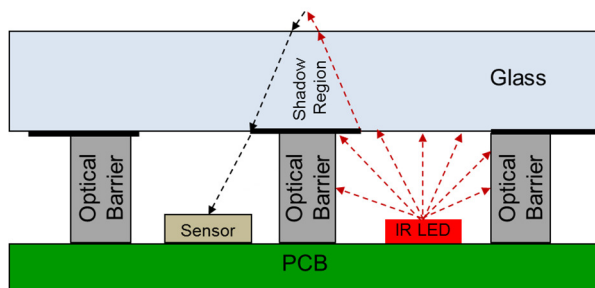


Figure 10a: Unfocused LED with Wasted Energy

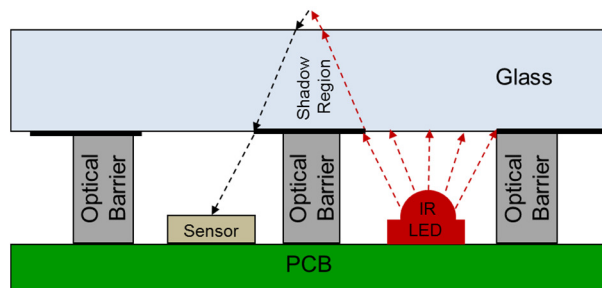


Figure 10b: Focused LED

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Using an LED having a narrow beam angle, coupled with an appropriate lens over the sensor is an effective way to greatly increase the maximum proximity sensing distance, at the expense of creating a narrower “field of view” within which objects can be sensed. More detail on the use of lenses can be found in design note DN36 Proximity Detection and Optical Lenses.

Very Close Proximity “Black Hair” Detection Issues

In certain applications it may also be necessary to detect objects that are placed against the glass surface. One classic problem arises when a proximity detector is “buried” in dense black hair. This requirement is the opposite of eliminating crosstalk. What is beneficial for eliminating crosstalk has a negative impact on detecting objects at a close distance.

One approach to this problem is to carefully design the optical apertures to create a well-defined critical point very close to but not below the glass surface. A well-defined critical point may require using a lens above the sensor and using a lensed LED, in conjunction with ink apertures, where the emission cone of the LED and detection cones of the sensor are properly designed. Another design note will go into lens design in detail.

The goal is to assure that the critical point occurs just outside the surface of the glass. That way, the 4% reflective outer surface of the glass will be inside of the critical point and will not provide a significant proximity signal (i.e. optical crosstalk). In between the glass outer surface and the critical point will be a “dead zone”, where objects will not be detected very effectively. This zone can be minimized through judicious design. Even dense black hair pressed up against the glass will have voids and gaps that will lie beyond the critical point, if the critical point is designed to lie just outside of the glass. Because the critical point is not actually a singular point, but is more of a “fuzzy point”; bringing the critical point progressively closer to the outside of the glass will generally cause an increase in optical crosstalk.

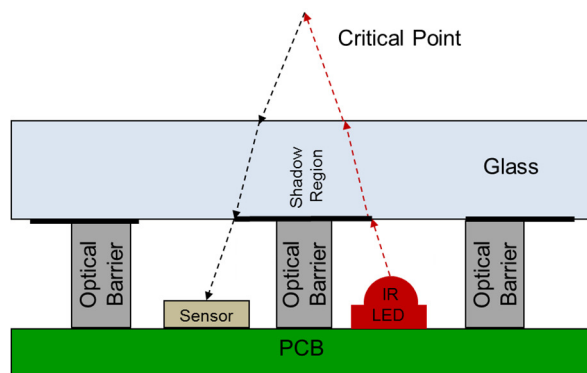


Figure 11a: Wide Strip with Far Critical Point

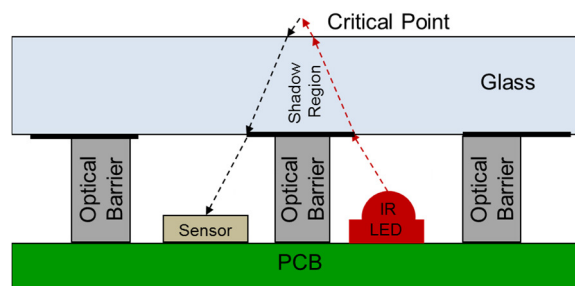


Figure 11b: Optimal Critical Point for Black Hair

Calculations with a Barrier

Many aspects of optical design have been discussed in general. In order to create an optimal design, the system must be properly engineered with accurate calculations. While the most optimal design (such as a system to detect black hair) should utilize an optical simulation system such as Trace Pro, significant design insights can be gained using the following calculations. Figure 12 shows the abbreviations for the various parameters of the system.

First, determine the angle from the sensor through the aperture. In this example, the angle is determined from the parameters of the design. If a lens is used over the sensor or LED, the angle may be defined by the lens design rather than the aperture. These calculations are for both the sensor and the IR LED.

Inside the glass, the angles of the rays change, in accordance with Snell's law of refraction. Using $n=1.5$ as the glass refractive index, compute the angle inside of the glass. This angle can be modified as it travels through the glass to determine the exit point for the light ray.

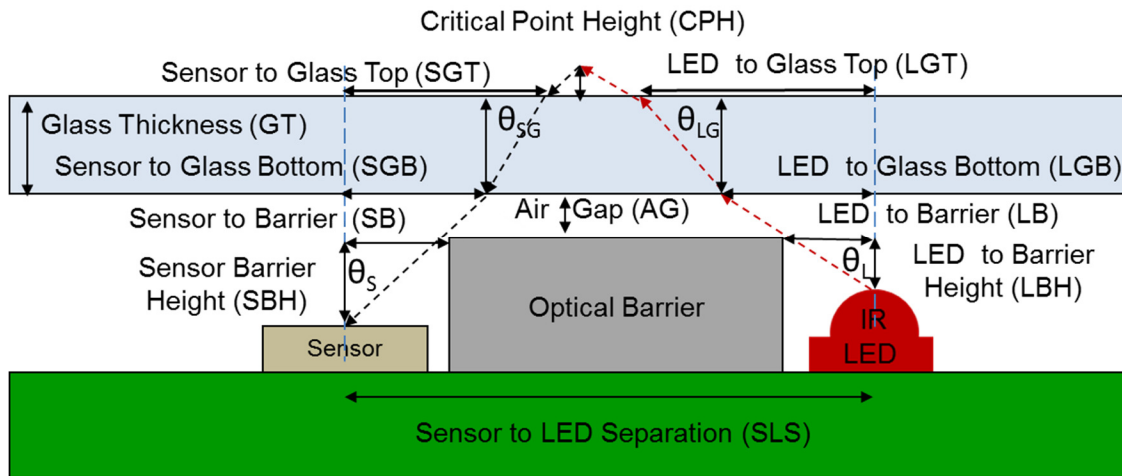


Figure 12: Parameters for Calculations with Barrier

Snell's Law: $n_{\text{air}} \cdot \sin(\theta_S) = n_{\text{glass}} \cdot \sin(\theta_{SG})$

$$\theta_S = \arctan(SB / SBH)$$

$$SGB = (SBH + AG) \cdot \tan(\theta_S)$$

$$\theta_{SG} = \arcsin[(\sin \theta_S) / 1.5]$$

$$SGT = SGB + GT \cdot \tan(\theta_{SG}) = (SBH + AG) \cdot \tan(\theta_S) + GT \cdot \tan[\arcsin(\sin \theta_S / 1.5)]$$

$$\theta_L = \arctan(LB / LBH)$$

$$LGB = (LBH + AG) \cdot \tan(\theta_L)$$

$$\theta_{LG} = \arcsin[(\sin \theta_L) / 1.5]$$

$$LGT = LGB + GT \cdot \tan(\theta_{LG}) = (LBH + AG) \cdot \tan(\theta_L) + GT \cdot \tan[\arcsin(\sin \theta_L / 1.5)]$$

$$CPH \sim \tan(\theta_S) \cdot (SLS - LGT - SGT) / 2$$

The goal of the design is to ensure the critical point lies outside the glass. In this case, the sum of LGT plus SGT must be less than the sensor to LED separation (SLS).

The following shows an example calculation with the following assumptions:

$$SBH = 0.8\text{mm} \quad LBH = 0.7\text{mm}$$

$$SB = 0.5\text{mm} \quad LB = 0.45\text{mm}$$

$$AG = 0.5\text{mm} \quad GT = 1\text{mm}$$

$$SLS = 2.4\text{mm}$$

$$\theta_S = \arctan(0.5 / 0.8) = \arctan(0.625) = 32^\circ$$

$$SGB = (0.8 + 0.5) \cdot 0.625 = 0.8125$$

$$SGT = 0.8125 + 1.0 \cdot \tan(32^\circ) / 1.5 = 0.8125 + 0.416 = 1.23\text{mm}$$

$$\theta_L = \arctan(0.45 / 0.7) = \arctan(0.64) = 33^\circ$$

$$LGB = (0.7 + 0.5) \cdot 0.64 = 0.77$$

$$\theta_{LG} = \arcsin[\sin(32^\circ) / 1.5] = \arcsin(0.35) = 21^\circ$$

$$LGT = 0.77 + 1 \cdot \tan(33^\circ) / 1.5 = 0.77 + 0.26 = 1.03\text{ mm}$$

For this example, the critical point is slightly above the glass.

$$CPH \sim \tan(21^\circ) \cdot (2.4 - 1.03 - 1.23) / 2 = 0.384 \cdot 0.14 / 2 = 0.027\text{ mm}$$

With manufacturing variations of +/- 0.2mm, the airgap must be reduced to a maximum of 0.3mm typical or the width must be increased by $0.2 / \tan(\theta_{SG})$ or about 0.3mm.

Calculations with a Dark Ink Stripe

The calculation can be slightly simplified when there is a black stripe on the glass, Figure 13.

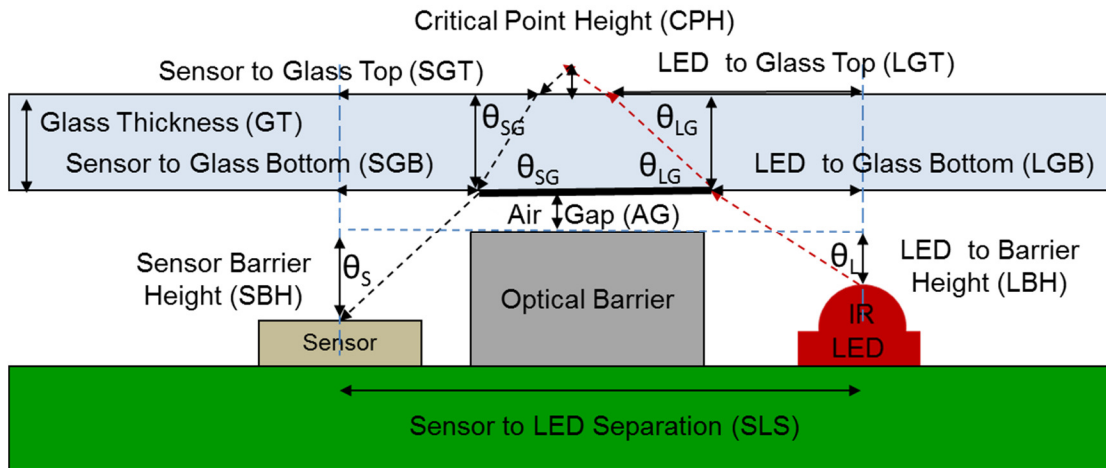


Figure 12: Parameters for Calculations with Black Ink Stripe

$$\begin{aligned}\theta_s &= \arctan (SGB / (SBH + AG)) \\ \theta_{SG} &= \arcsin [(\sin \theta_s) / 1.5] \\ SGT &= SGB + GT * \tan (\theta_{SG}) = SGB + GT * \tan [\arcsin(\sin \theta_s / 1.5)]\end{aligned}$$

$$\begin{aligned}\theta_L &= \arctan (LGB / (LBH + AG)) \\ \theta_{LG} &= \arcsin [(\sin \theta_L) / 1.5] \\ LGT &= LGB + GT * \tan (\theta_{LG}) = LGB + GT * \tan [\arcsin(\sin \theta_L / 1.5)]\end{aligned}$$

The following shows an example calculation with the following assumptions:

$$\begin{aligned}SBH &= 0.8\text{mm} & LBH &= 0.7\text{mm} \\ SGB &= 0.8\text{mm} & LGB &= 0.8\text{mm} \\ AG &= 0.5\text{mm} & GT &= 1\text{mm} \\ SLS &= 2.4\text{mm}\end{aligned}$$

$$\begin{aligned}\theta_s &= \arctan (0.8 / 1.3) = \arctan (0.615) = 32^\circ \\ SGT &= 0.8 + 1.0 * \tan (32^\circ / 1.5) = 0.8 + 0.39 = 1.2\text{mm}\end{aligned}$$

$$\begin{aligned}\theta_L &= \arctan (0.8 / 1.2) = \arctan (0.667) = 34^\circ \\ LGT &= 0.8 + 1 * \tan (34^\circ / 1.5) = 0.8 + 0.42 = 1.22\text{ mm}\end{aligned}$$

For this example, the critical point is below the glass top surface.

$$CPH \sim 0.625 * (2.4 - 1.22 - 1.2) / 2 = 0.615 * (-0.04 / 2) = -0.01\text{ mm}$$

To work with a 0.2mm margin, the strip width must be increased by $0.22 / \tan (\theta_{SG}) \sim 0.33\text{mm}$.

The minimal black ink strip can be calculated as follows:

$$SLS - SGB + LGB + 0.33 = 2.4 - 1.6 + 0.33 = 1.13$$

Conclusion

This design note has provided an overview of the crosstalk considerations involved in performing proximity detection behind glass. Use of an optical barrier can be very effective in quenching a majority of the optical crosstalk; however this does not necessarily handle the crosstalk caused by reflection from the top surface of the glass.

Optical crosstalk from the top surface of the glass can be controlled by calculating the position of the "critical point", and ensuring that this point lies just beyond the outside surface of the glass. The critical point can be moved above of the glass by decreasing the air gap, increasing the separation between the sensor and the LED, by the use of a lens over the detector and/or LED, by increasing the spacing between the ink apertures or reducing the thickness of the glass over the sensor.

Design of a proper system requires proper calculations and understanding of systems margins. In some cases, optical simulation can be used to design more accurate systems such as systems where black hair detection is critical. However, nothing is better than prototyping the actual system to do measurements and comparing them with the calculated or simulated results.