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INTELLIGENT OPTO SENSOR
Number 35

DESIGNER'S NOTEBOOK

Proximity Detection and IR Ink

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Overview

TAOS proximity sensors operate by flashing an invisible IR light towards a surface and measuring the amount of reflected energy from that surface. In many applications, the sensor and IR LED are hidden behind dark ink for aesthetic reasons. The properties of these inks have a major impact on the performance of the proximity sensors. This Designer's Notebook discusses the properties and performance characteristics of IR Ink as related to Proximity Detection.

Ink Characteristics

IR proximity sensors are typically placed under a protecting cover made of glass or plastic. In many cases, the glass is painted, or the plastic is tinted with ink to hide the sensor. For proper proximity operation, the protecting cover must transmit IR light while at the same time being largely opaque to the visible light. For this discussion, the subject is limited to ink on glass.

"IR Inks" are formulated by ink suppliers such as Teikoku or Seiko specifically to block much of the visible light while passing IR light. With the continued push for smaller devices and more integration, the distance between the proximity sensor and the IR LED are shrinking bringing out issues previously unknown. With close proximity of the two devices, ink properties are becoming increasingly important.

One key ink characteristic is transmission. The ink must transmit a significant amount of the IR light. In a proximity detector, a tiny beam of invisible IR light is transmitted from the device through the IR ink, which is then reflected from the target which again passes through the IR ink and back to the sensor. The ink attenuates the light in both transmit and receive paths. For example, if the ink transmission is 70% , 51% of the signal will be lost in the round trip.

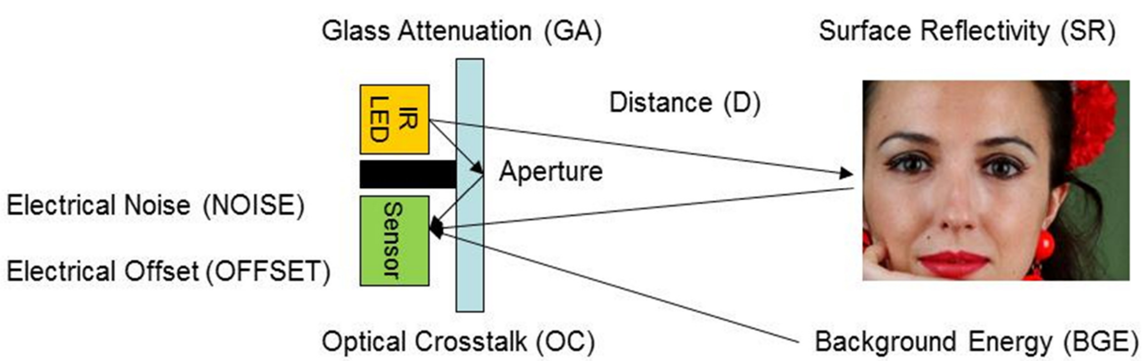

Figure 1. Factors Impacting Proximity Detection

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When light passes through a material, light is absorbed, reflected, scattered or transmitted. As stated, the IR light should be transmitted while the visible light is blocked. Visible light absorption is the preferred way to block light since the side effects are minimal; however, visible light absorption is difficult to control while passing IR light. Reflection is also an acceptable way to block light but is often closely related to scattering. Scattered light is the most problematic causing a small amount of the light to leak directly from the IR LED to the sensor.

Black ink typically absorbs light while white ink reflects/scatters light. In a very thin ink layer, some light will be transmitted, some absorbed, and some light reflected. With the black ink, the light not transmitted is absorbed. With the white ink, the light not transmitted is reflected.

There are two types of ink that will be discussed; they are "black" and "dark" inks. The term “black” ink refers to any ink, film, or other method used to conceal the electronics. Black ink typically does not transmit any light. The term “dark” ink refers to translucent ink, glass with tinting, film, or any other method used to partially hide the sensor. Dark ink allows light to transmit to the sensor.

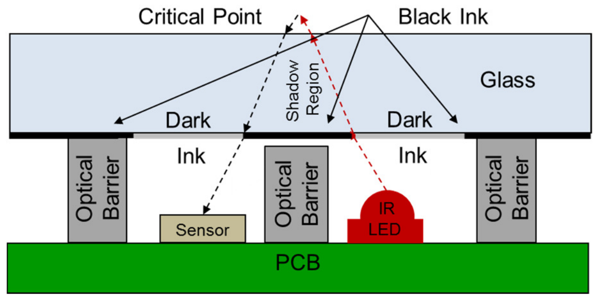

Figure 2. Black and Dark Ink

Figure 2 shows a system designed with the critical point just above the top surface of the glass to minimize optical crosstalk. Figure 2 also shows the “black ink” between the IR LED and sensor and the “dark ink” over the LED and the sensor. With the critical point outside the glass, the shadow region prevents light scattering on the inside top surface of the glass thereby reducing crosstalk significantly. Please refer to Designer's Notebook DN34 for additional details on designing the optical barrier and ink apertures to minimize optical crosstalk.

Scattering

While care is taken in designing the optical apertures and barriers, there remains a significant light scattering potential depending on the dark ink light scattering characteristics. Aperture design alone cannot block the scattered light. Scattering occurs on both the dark ink surface above the IR LED and the dark ink surface above the sensor. While the amount of scatter light is very small, the sensor is very sensitive detecting small reflections of scattered light off the glass.

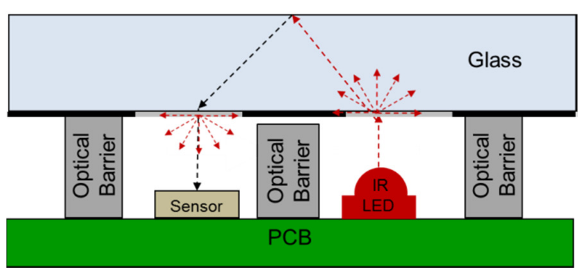

Figure 3. Light Scattering by Ink.

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To demonstrate that the crosstalk is from reflection on the top surface of the glass, an experiment using a drop of water is utilized. By placing a drop of water on the top of the glass, the index of refraction (water = ~1.33) more closely matched that of the glass (~1.5) allowing the light to exit the glass instead of reflecting back to the sensor.

Figure 4 below shows results based on the two configuration. The blue line depicts just the glass without water, and the red line depicts the glass surface with water drop present. The optical crosstalk is greatly reduced from 800 counts (blue line) to less than 200 counts (red line) with the water present. If the IR ink only covers the LED or only covers the sensor, the optical crosstalk is also reduced.

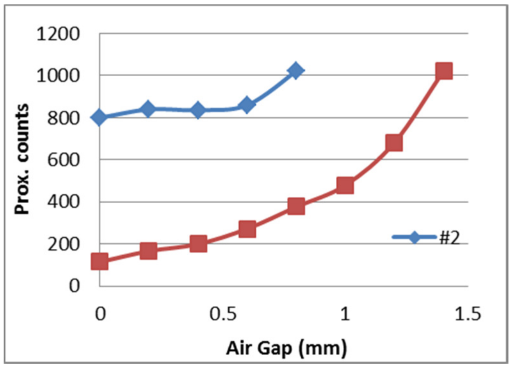
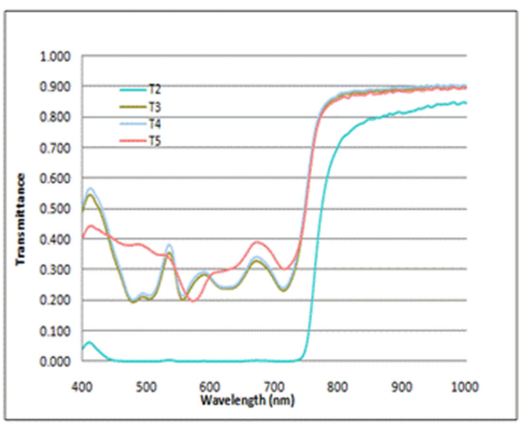


Figure 4. Drop of Water on Top of the Glass

IR Characteristics and Scattering

IR transmissive ink blocks visible light while allowing IR light to pass. Figure 5a shows measurements of four ink sample from Teikoku. All four inks have a transmission wavelength around 750nm. Sample T2 has very low transmittance in visible region, while the other three samples T3, T4, and T5 have about 20-30% transmittance in the visible.



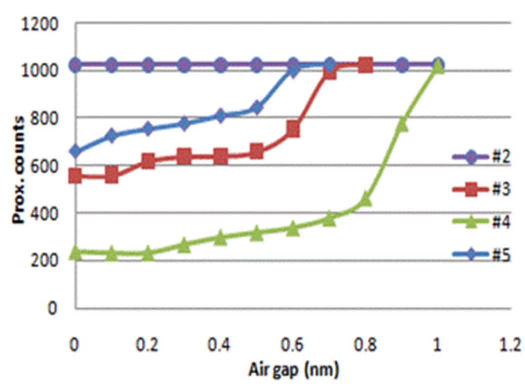


Figure 5a. Transmittance of Ink Samples

Figure 5b. Optical Crosstalk of Ink Samples

Figure 5b shows optical crosstalk of the four ink samples due to light scattering characteristics. The #2 ink has the worst crosstalk. Samples #3 and #5 have less crosstalk. Only, sample #4 looks acceptable with the lowest crosstalk.

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Wavelength Dependent Light Scattering

IR inks were investigated to determine their wavelength dependant light scattering characteristics. The four IR inks were organic pigment inks. Conventional light scattering is based on particle size and is described by the Rayleigh scattering or Mie scattering models. The IR inks investigated show a strong resonance scattering peak near their transition wavelength in Figure 6a. The total reflectance is reflection plus scattering.

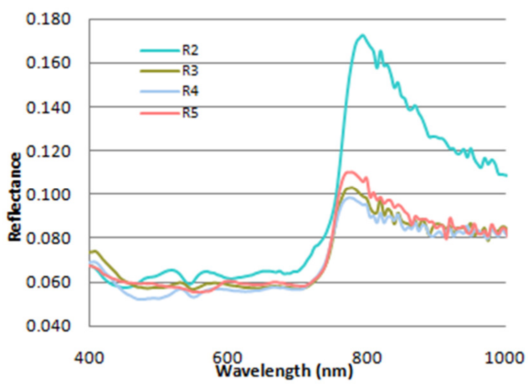

Figure 6a. Scattering Spectrum of IR Inks

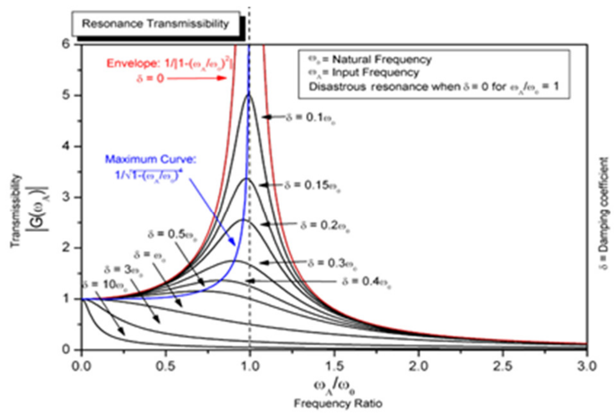

Figure 6b. Sample of Harmonic Resonance

The resonance scattering peaks shown in Figure 6a are similar to typical (mechanical, electrical, optical, etc.) resonances of simple harmonic motion as shown in Figure 6b (http://en.wikipedia.org/wiki/MechanicalResonance).

Theoretical Model of Bound Electron Scattering

Bound electron model is described by the equation:

$$m\ddot{x} = -m\omega_0^2 x + \frac{2e^2}{3mc^3}\dot{x} + eE_0 \cos \omega t$$

m is mass of electron, e is the charge of electron, x is the displacement, ω_0 is the resonance frequency, c is the speed of light, E_0 is the electrical field and ω is frequency of the field. Figure 8 shows the bound electron scattering model where strong scattering is shown at the resonance frequency.

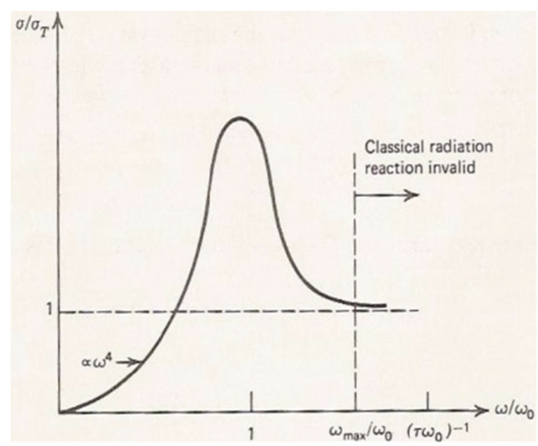

Figure 8. Bound electron scattering model (http://www.astro.rug.nl/~etolstoy/astroa07/)

This equation gives the solution of the light scattering cross-section of

$$\sigma(\omega) = \sigma_T \frac{\omega^4}{(\omega^2 - \omega_0^2)^2 + (\omega_0^3 \tau)^2}$$, here $\tau = 2e^2/3mc^3$.

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From this equation, we can see:

1. $\omega >> \omega_0$: $\tau(\omega) \sim \tau_T$ for incident energies much higher than binding energy of the electrons, so the electrons behave as if free. (Thomson scattering)
2. $\omega << \omega_0$: $\tau(\omega) \sim \tau_T \, (\omega/\omega_0)^4$ (Rayleigh scattering)
3. $\omega \sim \omega_0$: near resonance scattering. $\sigma(\omega) = \frac{2\pi^2 e^2}{mc} \frac{\Gamma/2\pi}{(\omega-\omega_0)^2 + (\Gamma/2)^2}$

Applying the Scattering Model to IR Inks

This model is applied to IR ink scattering as shown in Figure 9 below. The upper half of the Figure 9 shows the transmittance and the lower half shows the total reflectance which is specular reflection plus scattering. When the energy of the incident light is low (at longer wavelengths), the ink samples behave as Rayleigh scatterers with high transmittance, low absorption, and low scattering. When the energy of the incident light is high (at shorter wavelengths), the ink samples behave as Thomson scatterers where most light is absorbed with low transmittance and low scattering. When approaching the transition wavelength with the light frequency getting close to the resonance frequency of the inks, the inks transition from a transparent state to an opaque state and generate strong scattering characteristics. The inks all have a transition wavelength around 750nm, a resonance peak around 800nm, and a long tail extending to 850nm (which is wavelength of our LED). To reduce the scattering induced crosstalk, the LED wavelength should not be selected near the ink transition wavelength (750nm) but as far as possible away from it.

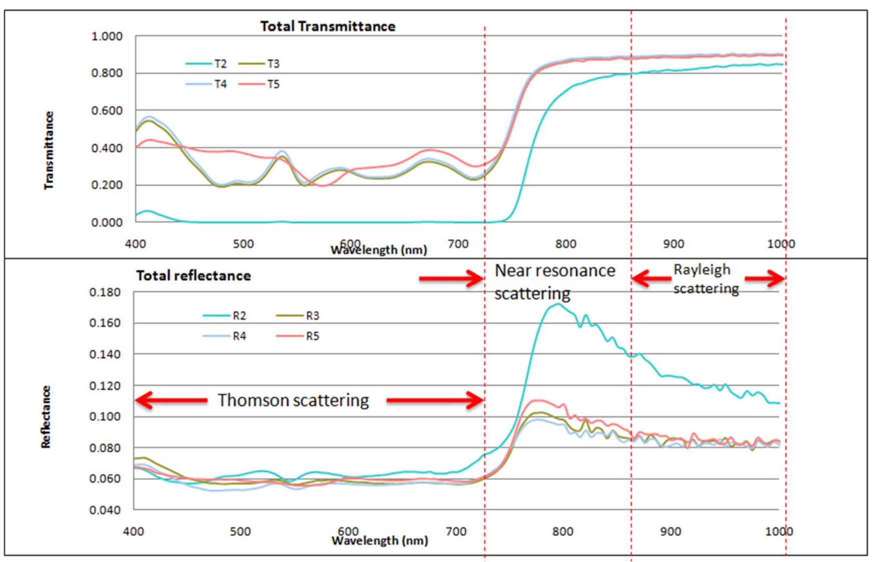

Figure 9. The IR ink scattering can be explained by bounded electron scattering model

Conclusions

Optical crosstalk generate by IR inks is due to near resonance scattering around the transition wavelength. To reduce scatter induced crosstalk, choose inks with a lower transition wavelength. For example with an 850nm LED, choose inks with a transition wavelength around 650nm~700nm instead of the current IR inks with transition wavelength around 750nm. In addition, the IR inks should have some transmission of the visible light; for example, about 20% transmission in the visible instead of less than 5% seen above which is typically related to the optical density of the ink.

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