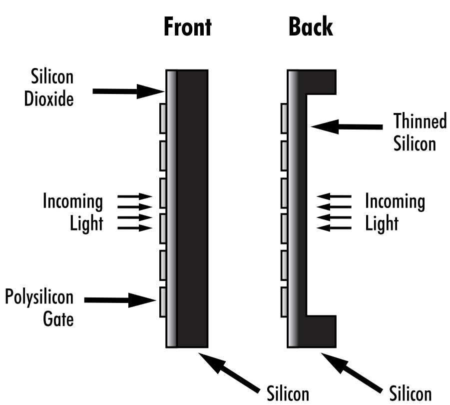

Figure 1. Comparison of front-illuminated and back-illuminated CCD.

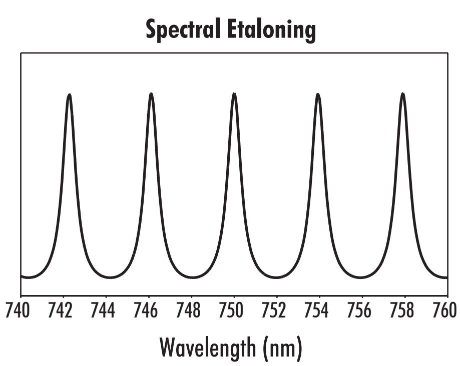

Figure 2. Example of spectral etaloning showing the variation in intensity (vertical axis) with wavelength.

Etaloning in Back-Illuminated CCDs

Introduction

Thinned back-illuminated CCDs (charge-coupled devices) are solid-state imaging devices that have been etched to 15-30 μm thickness in order to collect light through the back surface. As a result of this modification, no light is lost through absorption and reflection by the polysilicon gate structure and these CCDs have more than twice the quantum efficiency (light-detection ability) of their front-illuminated counterparts (see **Figure 1**). An unfortunate side effect of this process is that the devices become semitransparent in the near infrared (NIR). Reflections between the parallel front and back surfaces of these CCDs cause them to act as partial etalons. This etalon-like behavior leads to unwanted fringes of constructive and destructive interference, which artificially modulate a spectrum. The extent of modulation can be significant (over 20%) and the spectral spacing of fringes (typically 5 nm) is close enough to make them troublesome for almost all NIR spectroscopy. This note presents the theory of how etaloning occurs, as well as the solutions developed by Roper Scientific™ to combat this effect in back-illuminated CCDs.

Review of Etalons

An etalon is a thin, flat transparent optical element with two highly reflective surfaces that form a resonant optical cavity, and only wavelengths that fit an exact integer number of times between the surfaces can be sustained in this cavity. Because of this property, etalons can be used as comb filters, passing just a series of uniformly spaced wavelengths. In an imperfect etalon, the reflectance of the surfaces becomes less than 100% and the spectral characteristics soften from a spiky comb to a smooth set of fringes. Absorption between the surfaces also worsens the quality of the resonant cavity, which is measured by cavity finesse (see **Figures 2, 3 and 4**). Thus, the three factors that determine the shape and character of an etalon are d, the distance between the two surfaces; λ, the wavelength of the light; and Q, the finesse of the cavity, as shown in the following equation (where I is intensity):

$$I = \frac{I_{max}}{1+(2Q/\pi)^2\sin^2(2\pi d/\lambda)}$$

(Equation adapted from B. Saleh and M. Teich, *Fundamentals of Photonics*, John Wiley & Sons, New York, 1991)

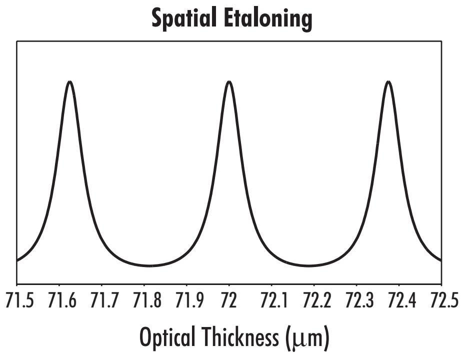

***Figure 3**. Example of spatial etaloning showing the variation in intensity (vertical axis) with thickness.*

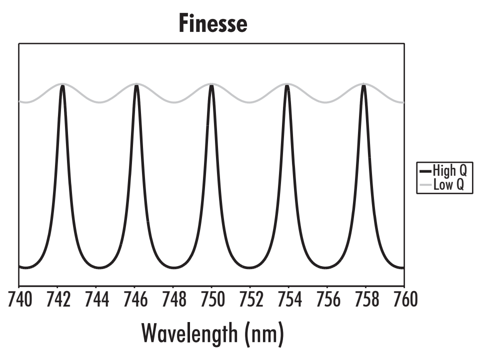

***Figure 4**. Example of etaloning showing the effects of finesse (Q) on the quality of the etalon.*

The Origins of Etaloning in a Back-Illuminated CCD

At NIR wavelengths, the silicon of which CCDs are made becomes increasingly transparent, causing the QE (quantum efficiency) to decline in the red. The back surface, where light enters a CCD in the back-illuminated configuration, is typically antireflection (AR) coated. These coatings are not perfect, however, and their effectiveness varies by wavelength. Most CCD back-surface antireflection coatings are not optimized for the NIR. For example, the reflection from the back surface of a CCD that is optimized for ultraviolet (UV) response is worse in the NIR than that from a CCD whose AR coating is optimized for longer light wavelengths.

Once light has passed through the body of a CCD and is about to reach the polysilicon electrodes, it encounters a sandwich of layers that generally includes silicon dioxide (refractive index 1.5). This sizeable discontinuity from the refractive index of silicon (which is 4) produces a large reflection back into the CCD. At wavelengths where silicon is transparent enough that light can traverse the thickness of the CCD several times, light bounces back and forth between the two surfaces. This increases the effective path length in the silicon (enhancing the QE) and also sets up a standing wave pattern. Amplitude is lost at both reflective surfaces and by absorption in the body of the silicon. However, at longer wavelengths sufficient amplitude survives to cause significant constructive or destructive interference.

While silicon is usually thought of as opaque, it must be remembered that a back-illuminated CCD is typically only 15 to 30 μm thick (less than a thousandth of an inch). A layer this thin can transmit a significant fraction of NIR light. For example, a back-illuminated CCD that is 17 μm thick (mechanically) would have the effective optical thickness of about 60 μm (since the refractive index of silicon in this wavelength range is 4). Thus, the round-trip optical path length between the surfaces is approximately 120 μm. At 750 nm, this would be 160 wavelengths. Therefore, there would be constructive interference at 750 nm. This pattern of interference would continue to repeat with intervals of about 5 nm.

In addition to the spectral source of etaloning, in a thin CCD there can also be spatial etaloning. The spatial pattern arises from the incidence of monochromatic light on an etalon whose thickness is not perfectly constant. A small variation in thickness can change the local properties from constructive to destructive interference. The change required is only a half-wavelength in the round-trip path length. Since the index of silicon is 4, the change in CCD mechanical thickness required to produce this optical effect is only about 1/16 of a wavelength, or 0.05 μm at a wavelength of 800 nm. This effect can actually be used to visualize how uniform the thickness of a CCD is. If a CCD had perfectly uniform thickness, the modulation due to spatial etaloning at a given wavelength would disappear. All pixels would have the same degree of constructive or destructive interference at a given wavelength.

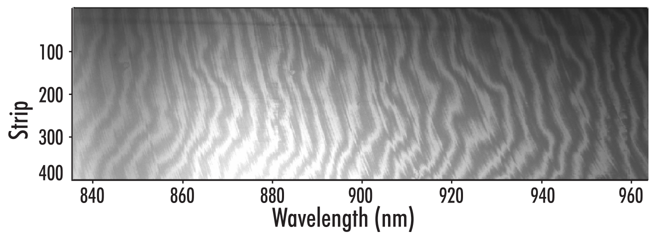

Figure 5. Image from a back-illuminated CCD camera showing combined spectroscopic and spatial etaloning.

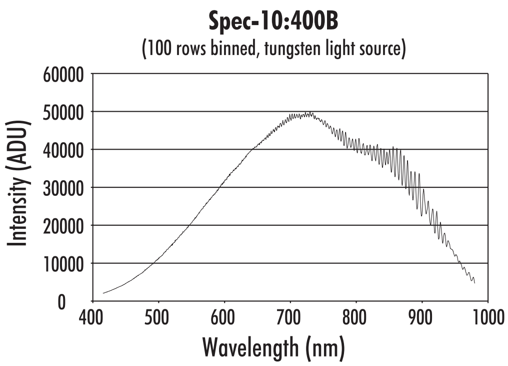

Figure 6. Spectrum of a tungsten light source using a back-illuminated CCD camera system. The etaloning becomes most pronounced between 800 nm and 1 µm, but is apparent even at 700 nm. ADU=arbitrary data unit.

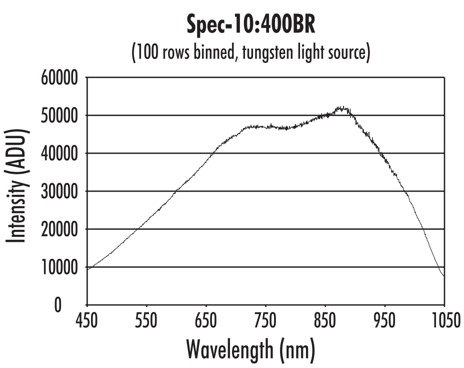

Figure 7. Spectrum of the same tungsten light source using a Princeton Instruments Spec-10:400BR (NIR-enhanced) high-performance CCD camera system. Note the improved QE and the effective removal of etaloning, even above 1 µm.

In most imaging applications with back-illuminated CCDs, spatial etaloning is not evident because the applications are at shorter wavelengths, where the silicon absorption damps out the etalon effect. In addition, many applications use light that is spectrally broad enough to span (and average out) several etalon-fringe cycles. The latter requires only a spectral bandwidth of a few nanometers. In a spectrometer, by comparison, the light on any one column of pixels is very narrow spectrally, typically less than 0.1 nm. Thus, this spectral bandwidth is much less than the period of etalon cycles (~5 nm). As a result, spatial etaloning is quite evident when viewing an image of a uniform spectrum (e.g., tungsten bulb) in the NIR (see **Figure 5**).

Spectroscopic etaloning is related to, but different from, spatial etaloning. It derives from the fact that in a spectrometer the wavelength of light varies across the CCD. Thus, even if a back-illuminated CCD was available with absolutely uniform thickness, it would still show fringes due to this etalon effect. The fringes in this case are due to the variation of the wavelength, not the thickness. As a result, when a spectrum is dispersed across a back-illuminated CCD, the characteristic comb pattern will be superimposed on the normal response.

How to Avoid Etaloning

Etalon effects do not occur in front-illuminated CCDs due to the greater thickness of these devices (typically 600 µm) and the corrugated nature of their polysilicon surfaces (refer to **Figure 1**). Front-illuminated CCDs can now be manufactured with moderate QE and are a practical detector option for applications at wavelengths where silicon is nearly transparent (over 900 nm) or for multistripe spectroscopy.

The reduction of etalon fringing by using a very low f/# spectrometer might seem to be a solution in that light rays entering the CCD at somewhat different angles would travel somewhat different path lengths and average out constructive and destructive effects. However, this remedy for etaloning turns out to be ineffective because the high refractive index of silicon (which is 4) refracts a converging beam into one that is much closer to parallel (e.g., an f/4 beam entering a CCD becomes about f/16 inside). At these narrow angles, the path-length differences are below the required fraction of a wavelength.

In a spectroscopic application using a back-illuminated CCD, both spatial and spectroscopic etalon effects occur. These are additive, however, which is helpful because the pattern of spatial etaloning is generally not aligned with the columns of the CCD. Spectroscopic binning along the columns tends to average out some of the constructive and destructive interference.

One technique to reduce spectrum modulation due to etaloning is to spread the light out over many rows of a CCD (preferably all of them) and then to bin the whole CCD into one spectrum. This method is sometimes practical and can also help increase sensitivity of the system by offering maximum light-collection area. However, cooling of the CCD must be adequate (i.e., liquid nitrogen) to overcome dark-current load incurred by combining the dark current of all the rows. For experiments in which the light is collected with a single optical fiber, it may be advantageous to spread the light out vertically on the CCD by intentionally using a non-imaging spectrometer.

Princeton Instruments Spec-10™ BR Detectors

The best possible means of reducing etaloning effects is to design a back-illuminated CCD that minimizes the sources of the etaloning. To accomplish this, Roper Scientific has worked with CCD vendors to develop an exclusive, superior back-illuminated CCD design that has maximum etalon reduction (see **Figures 6 and 7**). It combines three key features:

1. The CCD is made of thicker silicon, roughly double the thickness of a normal back-illuminated CCD. This contributes significantly to the absorption of NIR light, reducing the amount of light that survives a round-trip path to cause interference and increasing the QE.

2. The AR coating has been optimized for NIR wavelengths, reducing the amount of light reflected into the CCD when the light returns to the CCD back surface from the polysilicon side. It also increases the amount of light that passes into the CCD initially, thereby increasing the QE and reducing stray light in the spectrometer.

3. The CCD back surface of the Spec-10 BR series is processed in a proprietary manner that helps to break up the etalon effect.

The combination of these approaches has resulted in a state-of-the-art CCD design that is uniquely suited to low-light NIR spectroscopy applications. The Spec-10:100BR and Spec-10:400BR incorporate all of these features in a spectroscopic format with very low noise and exceptional sensitivity from the UV to the NIR. These innovative high-performance CCD cameras are available only from Roper Scientific.

Contact **Roper Scientific, Inc.** for more information:

3660 Quakerbridge Road Trenton, NJ 08619
tel: 609.587.9797
fax: 609.587.1970
email: info@roperscientific.com
web: www.roperscientific.com

3440 East Britannia Drive Tucson, AZ 85706
tel: 520.889.9933
fax: 520.573.1944
email: info@roperscientific.com
web: www.roperscientific.com

530 Main Street Acton, MA 01720
tel: 978.263.3584
fax: 978.263.5086
email: mail@acton-research.com
web: www.roperscientific.com

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