Interferometric microscope with true color imaging

J. L. Beverage, X. Colonna de Lega*, M. F. Fay
Zygo Corporation, Laurel Brook Road, Middlefield, CT 06455

ABSTRACT

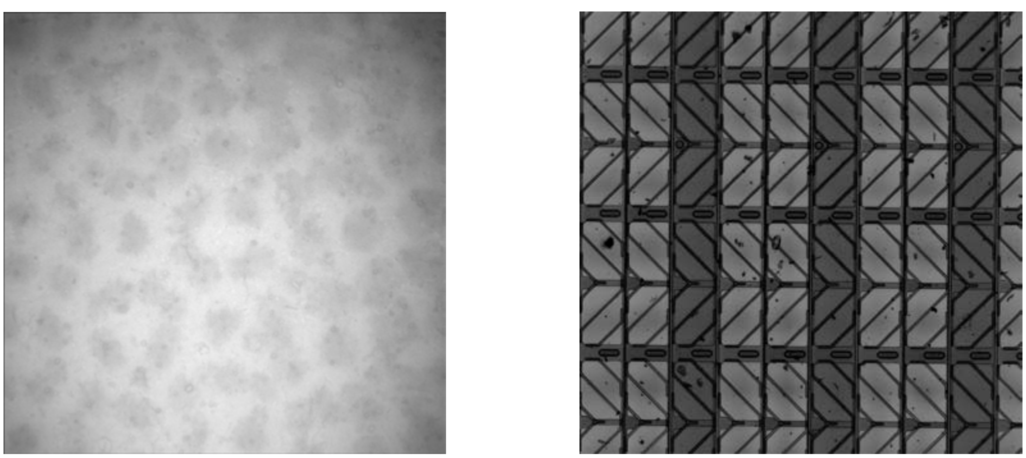
Optical 3D profilers based on Coherence Scanning Interferometry (CSI) provide high-resolution non-contact metrology for a broad range of applications. Capture of true color information together with 3D topography enables the detection of defects, blemishes or discolorations that are not as easily identified in topography data alone. Uses for true color 3D imaging include image segmentation, detection of dissimilar materials and edge enhancement. This paper discusses the pros and cons of color capture using standard color detectors and presents an alternative solution that does not rely on color filters at the camera, thus preserving the high lateral and vertical resolution of CSI instruments.

Keywords: coherence scanning interferometry, color imaging

1. INTRODUCTION

1.1 Coherence scanning instruments are typically color-blind

Coherence Scanning Interferometry (CSI)[1,2] provides high-resolution non-contact surface structure analysis for a broad range of applications. Most commercial instruments of this type rely on a low-coherence light source to generate the localized interference signals required for surface height characterization. In general, this limited coherence is due to the broad spectral width of the light source, for example a “white-light” Light Emitting Diode (LED), which generates light over most of the human visible spectrum. However, the spectral information that enables metrology is traditionally not used to derive colorimetric characteristics of an object surface. So while a conventional CSI instrument shares most attributes of a wide-field imaging microscope, it lacks the ability to image the true color of the surface. For instance, Fig.1 shows gray level images of printed paper and color filters. While the intensity data provide some information about the spatial distribution of features on these surfaces, they do not readily discriminate between different types of ink pigments or color filters. The same limitation exists for the corresponding topography data.



(a) (b)

Figure 1. Intensity data captured by a CSI instrument for (a) ink pigments on high-gloss paper and (b) an array of color filters for flat panel displays.

* xcolonna@zygo.com; www.zygo.com

1.2 The benefits of color information

Surface color is generally not required for conventional surface metrology where one is looking for form, waviness, roughness or some other dimensional quantity. There are however applications where the addition of color information is useful, either by improving the user experience or by revealing an attribute of the surface not discernible in the conventional height or intensity data. For example, topography and color data can be combined to render natural-looking 3D images of a part, while color data alone facilitates the detection of defects, blemishes or discolorations that are otherwise invisible in a topography map. Other uses include image segmentation, detection of dissimilar materials and edge enhancement.

The value of the color information as a companion to surface metrology has been recognized in recent years, for example by manufacturers of laser scanning confocal microscopes. In this case a color sensitive camera is combined with through-the-lens illumination and a broadband source such as a white-light LED.[3,4] The color information together with the in-focus topography data collected by the monochrome laser scanning module produces a 3D image of a sample. Newer instruments use pulsed light sources operating at three different wavelengths to perform the confocal detection,[5] collecting color information during the confocal data acquisition.

2. OPTIONS FOR ADDING COLOR IMAGING TO CSI INSTRUMENTS

2.1 Performance tradeoffs

Adding color imaging to a CSI instrument affects its design and may require trading off some of its standard performance in exchange for the added data gathering capability. A key benefit of scanning instruments such as CSI, confocal or focus sensing microscopes is their so-called "infinite focus" characteristic, where data are always collected at the position of best focus, independently for each pixel. As a consequence, the measurement volume covered by the instrument is independent of the depth-of-focus of the optics. This important characteristic must be preserved when collecting color information since a single color snapshot captured at some average focus location would result in unacceptable image blur.

Some of the key performance attributes of CSI metrology tools are listed in Table 1. The second column in the table summarizes the main factors that define or limit practical performance. Line items in italic map to characteristics of the detector used for data collection.

Table 1. Key performance attributes of coherent scanning surface profilers and dependency on system components.

Performance attribute[6]	**Dependency**
Measurement noise	*Detector read noise and full well capacity* Scanner fidelity Vibration, turbulence
Lateral (optical) resolution	Mean source wavelength Numerical aperture
Lateral (pixel) sampling	System magnification *Detector pixel dimensions*
Field of view	System magnification *Detector pixel count*
Measurement throughput	*Maximum possible detector frame rate* Maximum scanner velocity

In an ideal case the basic performance attributes listed above would be unaltered by the addition of color imaging. In practice, the enabling technologies have physical limitations that will require making compromises compared to an otherwise equivalent color-blind or monochrome instrument. The next sections discuss a few possible options and highlight their respective tradeoffs.

2.2 Color-filter-based cameras with broadband illumination

The most straightforward solution to providing color imaging capability to a CSI instrument is to replace its monochrome detector array (CCD or CMOS) by one equipped with a mosaic of color filters lined up with its pixels. This approach provides a simple path for conversion as many camera vendors offer both camera versions for a given base detector. There is quite a variety of possible filter patterns, starting with the widely-used Bayer pattern.[7] Fig. 2 shows examples of color filter arrays, using red, green and blue filters, sometimes combined with open or "white" pixels.

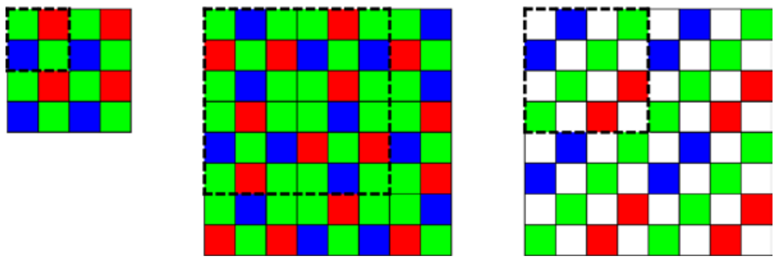


Figure 2. Example of 2x2, 6x6 and 4x4 color filter mosaics in use on color cameras. The dashed line delimits the elementary pattern.

The raw image produced by such detector arrays contains a subset of the actual color information available at each light-sensitive element. So-called "de-mosaicing" interpolation algorithms convert the sub-sampled information into color data at each image location. Not surprisingly, such data sampling and processing limits the effective sensing resolution of the detector array compared to a monochrome array with equal pixel dimensions.[8,9] Additional limitations include the emergence of moiré patterns when imaging dense periodic structures, rainbow artifacts along monochrome slanted edges and azimuth-dependent color response.

An option for compensating the loss of sampling resolution is to increase system magnification. For instance, assuming a pixel on a monochrome detector is matched to the diffraction spot of the optical system, doubling system magnification allows placing the G, R, G and B pixels of the Bayer-filter equivalent array within the same diffraction spot. In this case the overall system resolution is nearly matched, if somewhat imperfectly, for the two systems. The tradeoff is a reduction of the field of view by a factor of two. Achieving the same field of view then requires using a detector with four times the number of pixels. As a rule of thumb this larger detector will not deliver the same maximum frame rate as the reference monochrome array, may be noisier, and/or will be substantially more costly.

The considerations discussed above for straight intensity imaging also affect the collection of metrology CSI data. If de-mosaic data are used, one has to study the effect of the interpolation algorithm and assess the likelihood of signal envelope or phase distortions.

In summary, swapping a monochrome camera by its color-filter equivalent is a convenient path for conversion to a color-enabled CSI instrument, but necessarily implies some loss of lateral resolution, precision, or throughput.

2.3 Multi-color-channel cameras with broadband illumination

Most of the resolution issues highlighted above for spatially distributed color-filter cameras disappear when using a camera that simultaneously captures color information at each pixel location. A first class of devices offers this capability by splitting the incoming light into three distinct optical paths, allowing the use of three distinct monochrome detectors, as shown in Fig. 3. This technical approach originated in broadcast television equipment before being adopted for high-end camcorders and industrial cameras. The registration tolerances of the three detectors are typically better than half a pixel width.

Some of the drawbacks of these devices are the limited choice of detector resolution and size (for commercial devices), the relative bulk of the resulting cameras, the need for custom imaging lenses designed to compensate for the additional propagation in glass, some amount of spectral overlap between channels and frame rates that are generally slower than state-of-the-art industrial cameras. Another drawback is the high cost of the integrated device given the need for multiple detector arrays and electronics.

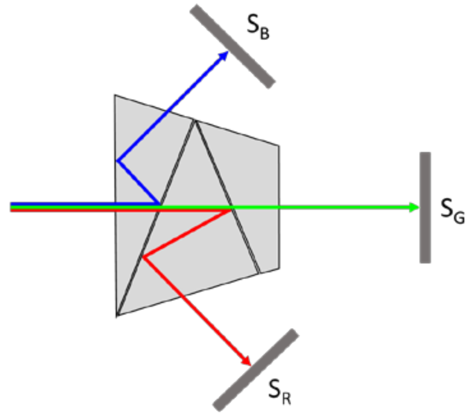


Figure 3. Principle of prism-based color channel separation for multi-detector color camera.

A second class of devices is based on detectors that have the ability to separate - within each pixel - photoelectrons that correspond to different energy bands of the incoming photons.[8,9] For instance, longer wavelengths propagate deeper within the silicon based pixel structure before being absorbed, while blue photons tend to be detected closer to the entrance interface. The main drawbacks of this solution are the very limited choice of pixel size and total pixel count, and the rather slow achievable frame rate. Spectral leakage between channels must be carefully considered as well.[10]

In practice, the limited variety of cameras using either of these technologies restricts the range of fields of view or sampling density that can be offered in a product. When a match is found, camera frame rates are generally an order of magnitude lower than what a state-of-the-art monochrome detector can offer. So while this category of devices solve the lateral-sampling issue of the filter-array detectors, this is at the cost of a very limited choice of practical devices and rather limited measurement throughput.

2.4 Dedicated data collection and analysis solution

The solutions discussed so far, while workable, either compromise key performance attributes of the CSI instrument or severely limit the choice of detector sizes that can be used in a color-enabled instrument. This is especially limiting when one looks at how rapidly device capabilities evolve, with many cutting-edge industrial cameras operating at around 1 gigasample per second (say 1024 x 1024 pixels at 1 kHz). Because not all of these devices provide the response linearity and spatial and temporal noise characteristics required for acquiring interference signals, only a subset of those detectors are appropriate for a high-end metrology instrument.

Starting from the overarching goal of using the best-performing cameras for metrology, we developed a proprietary solution for acquiring color information. The detector itself can be any type of monochrome device. There are no color filters at the pixel plane. The instrument design remains similar to that of a monochrome tool, see Fig. 4, with the main difference found in the more complex illuminator and supporting firmware. The illuminator includes multiple LED's that synthesize a variety of illumination spectra in support of different measurement modes. For instance, in a baseline mode of operation the illuminator generates an optimum spectral distribution for low-coherence interferometry. In this case the tool operation and performance is identical to that of an otherwise equivalent color-blind instrument.

When a user requests color information, the instrument first acquires surface metrology data in the conventional CSI mode and then collects additional information with a different illumination modality where red, green and blue color channels are synthesized sequentially. The color information is collected at the position of best-focus for each pixel, using the metrology data to determine the optimum location within the measurement volume. Proprietary algorithms combine the raw multi-channel data with calibration data collected beforehand to create surface reflectivity RGB triplets within the sRGB color space.

Harnessing the high frame rate of state-of-the-art cameras, the system can also collect and render color data in real time, providing the user with a live color stream when navigating over a sample.

This approach necessarily results in a modest reduction in overall measurement throughput, since metrology and color data collection are separate. Color acquisition is on average twice as fast as metrology data acquisition so the overall throughput hit is less than 50% given other overheads. This compromise is the price to pay for fully preserving the other key performance metrics: lateral resolution and sampling, measurement precision and field of view. Furthermore, the throughput limitation only applies when color data are requested. Otherwise the instrument offers the throughput of standard CSI.

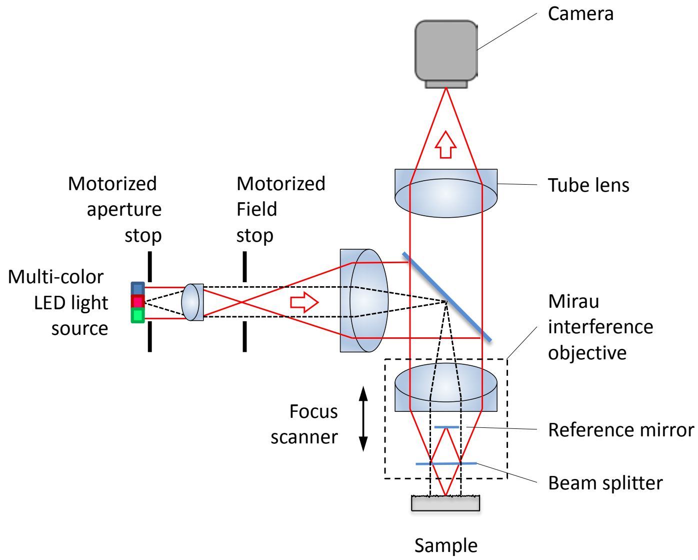


Figure 4. Simplified sketch of color-imaging CSI instrument, using a monochrome camera and a multi-LED illuminator.

3. EXPERIMENTAL DATA

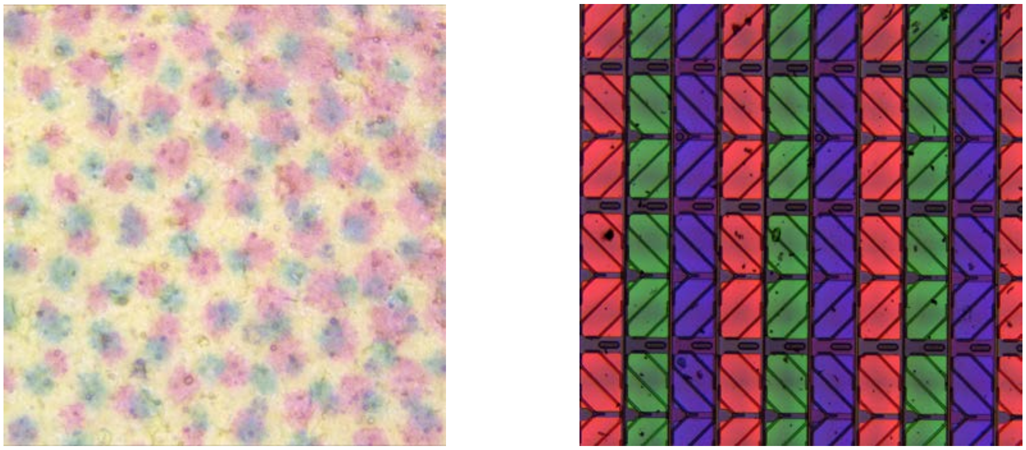
The next sections illustrate the benefits of color information for a variety of inspection applications. These data were captured with an instrument[11] equipped with the color capture solutions outlined in section 2.4.

3.1 Inspection and identification of color features

The color data of Fig. 5 reveal the location of the colored features hidden in Fig. 1. The high-gloss paper data were collected with a 10X Mirau objective and 0.5X tube lens while the color filter data were acquired with a 20X Mirau objective and 1X tube lens. Each image consists of one million RGB triplets.

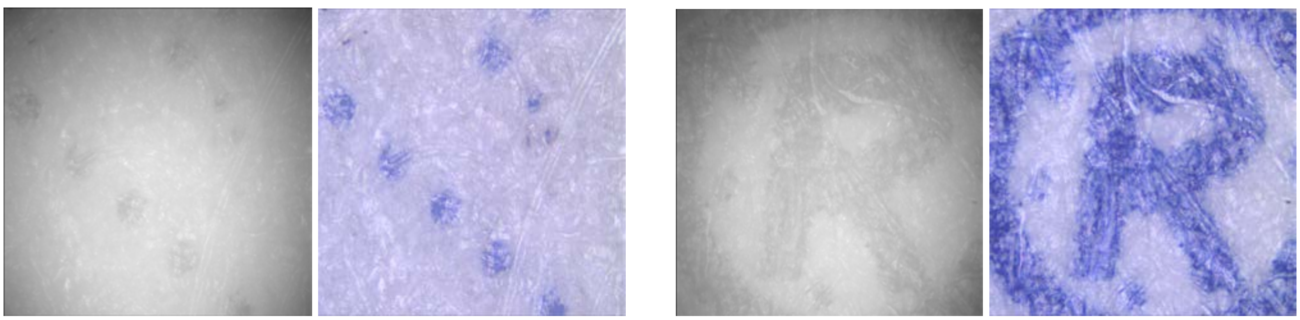
Fig. 6 shows examples of printed ink features that are normally invisible to the unaided human eye but become visible when the document is scanned or duplicated with a copy machine. A typical application is for “security” paper used in bank notes, checks, paychecks and other official documents. The figure shows both the monochrome intensity pattern discerned by the instrument and the corresponding color data. There is no indication of the presence of the pigments in the topography data, which only show tangled paper fibers.

The color information can be combined with corresponding topography data to generate a realistic-looking 3D image of the sample surface. Fig. 7 shows one such example for a piece of metallic wrapping paper measured with a 20X Mirau objective.



(a) (b)

Figure 5. Intensity data captured by a CSI instrument for (a) ink pigments on high-gloss paper and (b) an array of color filters for flat panel displays. These images match those of Fig. 1.



(a) (b)

Figure 6. “Invisible” ink pigments on security paper. (a) shows monochrome and color data for ink dots that will appear in the scanned image of a bank note or check but are otherwise invisible to the unaided eye. (b) shows a “registered” symbol.

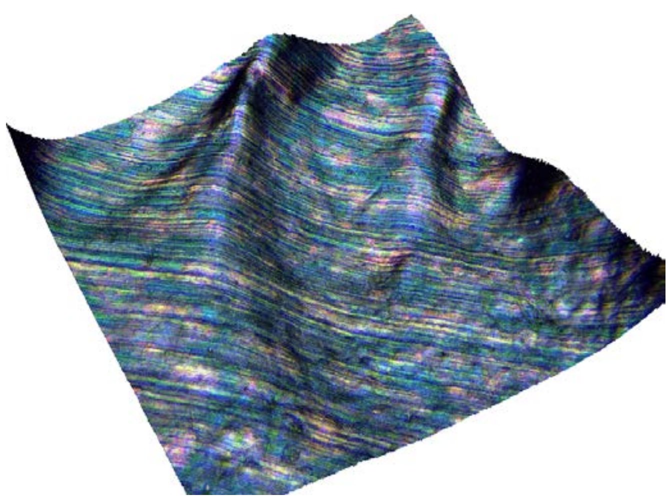
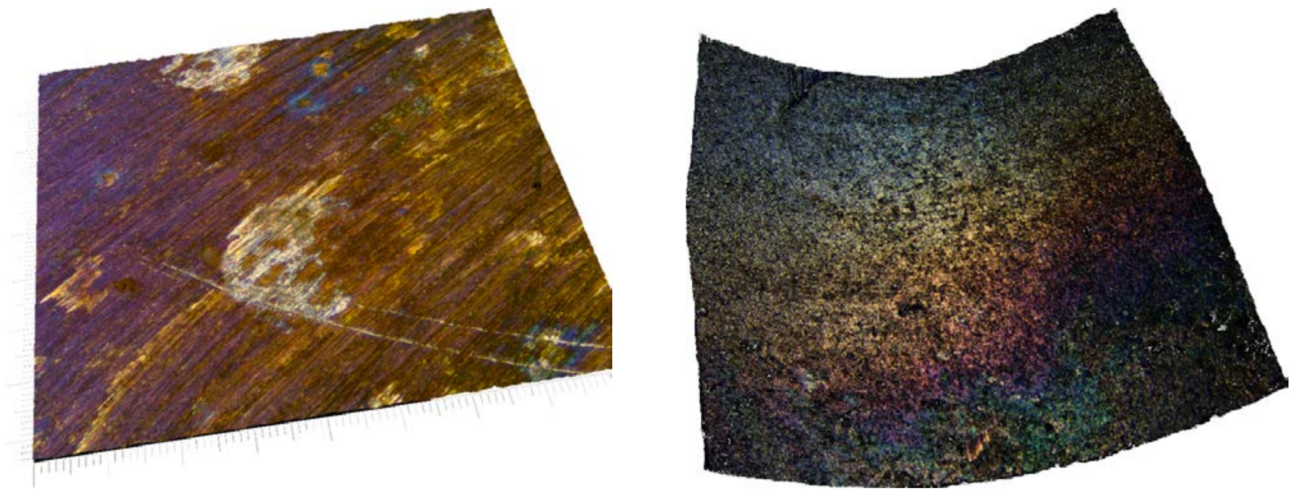


Figure 7. Hybrid map combining surface topography with measured color reflectivity for a piece of metallic wrapping paper. The field of view is about 850 µm on the side and the height range about 32 µm.

3.2 Inspection and identification of surface blemishes, corrosion or burnishing on metal parts

CSI is an important metrology asset for the machined-part industry owing to its resolution, speed and high sampling density compared to conventional tactile profilers. Both CSI and tactile profilers are routinely used to characterize surface finish (form, waviness, roughness, bearing ratio, etc). However, certain features of interest such as discolorations do not always print through in the topography or intensity data. Discolorations and blemishes can be indicative of manufacturing process variations or relate to localized wear or heating of a component. Color information can play a useful role in identifying such defects, as illustrated in Fig. 8.



(a) (b)

Figure 8. (a) 0.8 mm x 0.8 mm hybrid topography and color map showing local blemishes on a machined surface. (b) 1.7 mm x 1.7 mm hybrid map showing discoloration of a conical valve seat as a result of heat treatment.

Color information can also be useful in detecting corrosion. Fig. 9 shows wear marks and corrosion on two different U.S. pennies.

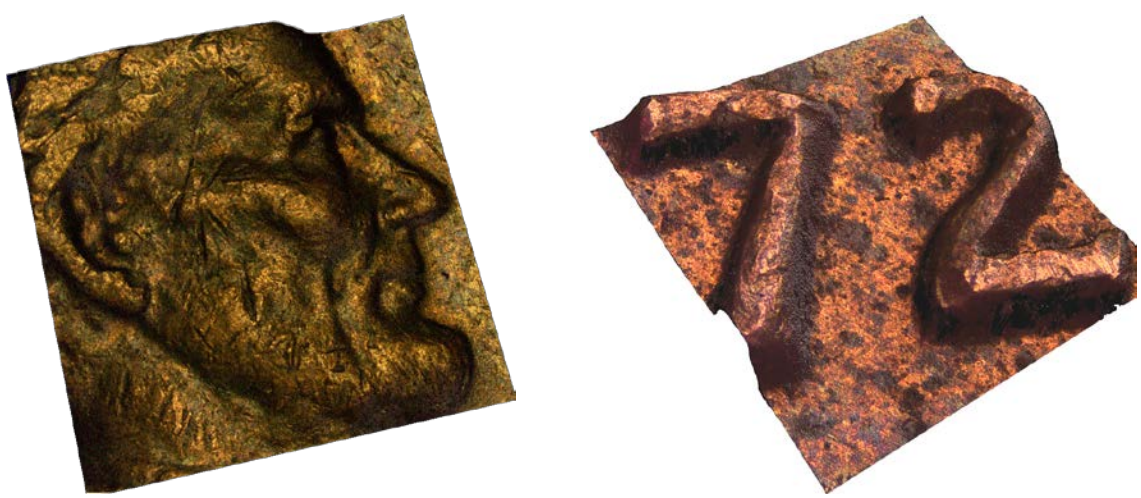
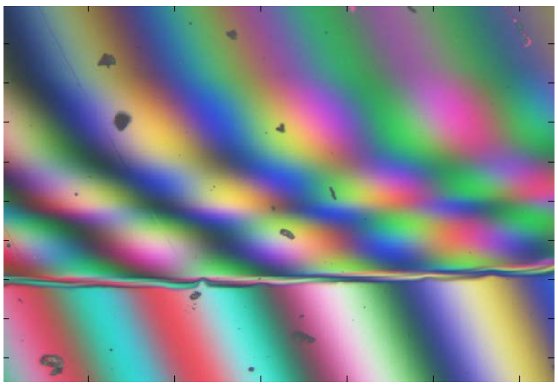


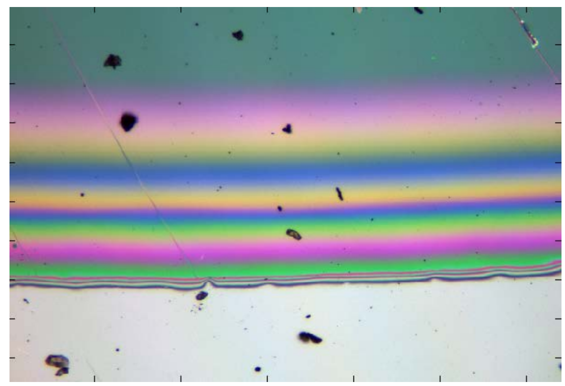
Figure 9. Details of two U.S. pennies showing wear marks and corrosion.

3.3 Visualization of transparent films

We stated in the introduction that using monochrome detectors has for a very long time hidden the color features of the sample under test, despite light sources spanning most of the visible spectrum. In fact, the inherently colorful nature of low-coherence interference patterns themselves has also been hidden. The optical engineers among us enjoy being able to “see” the achromatic fringe created by low-coherence interferometers, as seen in the lower part of Fig. 10(a) on bare silicon substrate. The upper part of the figure is even more colorful as the result of the overlap of the interference signal and Newton fringes created by a silicon dioxide layer about 1-µm thick near the top of the image, tapering down to zero in the lower third of the picture. Moving the microscope objective slightly out-of-focus yields the image seen in Fig. 10(b) where the colors bands are now only due to the presence of the transparent film, as if the instrument was a simple non-interferometric microscope.



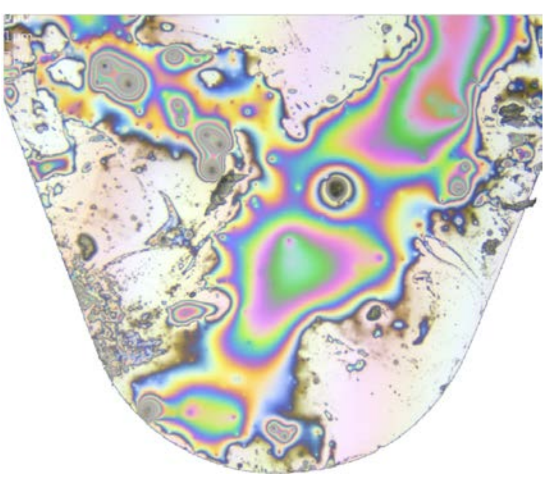
(a)



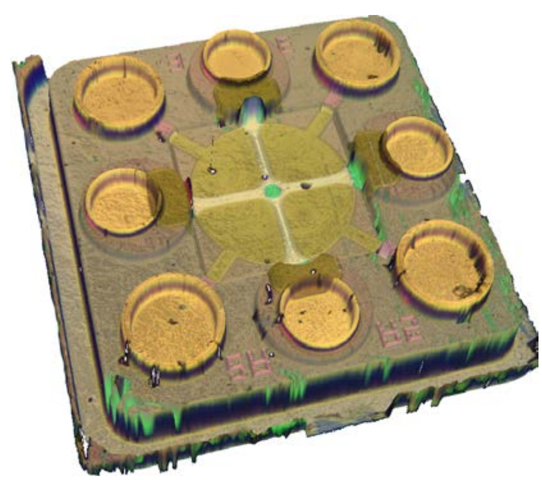
(b)

Figure 10. (a) Interference pattern overlaid with silicon dioxide film on silicon. (b) Same sample without fringes.

The ability to detect the presence of films and estimate their thickness by simple visual inspection is another side benefit of color imaging. Fig. 11(a) clearly shows that an oil film is present on the front of a cutting tool. In a more complex case, the abrupt change in color of the MEMS microphone sample in Fig. 11(b) indicates a film delamination at all bright green locations.



(a)



(b)

Figure 11. (a) Cutting tool with oil film (0.9 mm x 0.9 mm). (b) MEMS microphone sample exhibiting film defects where green (1.4 mm x 1.4 mm; 13-µm vertical range).

Fig. 12 shows areas encompassing one or more dies on three different semiconductor wafers. Color patterns are due to material absorption, dense periodic patterns diffraction and transparent films spectral filtering.

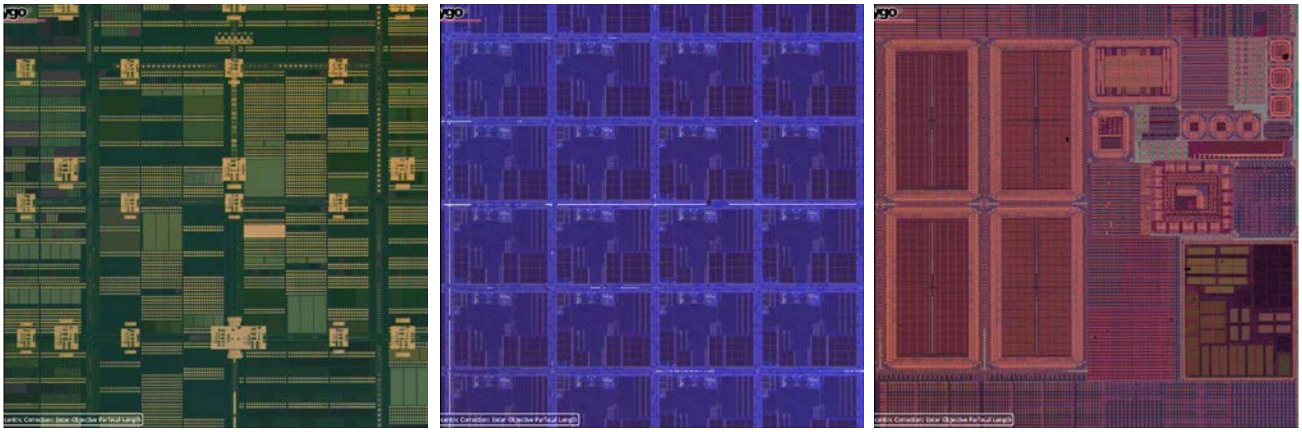


Figure 12. Examples of semiconductor wafers imaged in color as part of a CSI measurement. The field of view is 16.7 mm x 16.7 mm.

4. SUMMARY

As we have seen, there are several options for adding color imaging to CSI instruments. The typical CSI platform already includes most of the required hardware components, with the exception of the multi-color detector. While a few types of color imagers exist that could be used for the task, we found that their use implied unacceptable sacrifices with respect to key performance metrics. For instance, filter-based detectors substantially affect the lateral sampling of the instrument, while multi-detector cameras generally preclude using the cutting-edge devices that are most appropriate for high-throughput, high-resolution surface metrology. Our solution[12] provides color imaging capability by using a flexible multi-LED illuminator. This leaves all detector options available and guarantees that the CSI metrology performance is identical to that of an equivalent monochrome instrument. Measurement throughput is reduced only slightly when color data are actively acquired.

ACKNOWLEDGMENTS

The original work presented in this paper benefited from key contributions and input from Jim Biegen, Jeremy Wise, Dave Bourque, Scott Mitchell, Eric Felkel, Nate Gilfoy, Jeff Tinker, Peter Kuschnir and Peter de Groot.

REFERENCES

[1] ISO, [25178-604:2013(E): Geometrical product specification (GPS) – Surface texture: Areal – Nominal characteristics of non-contact (coherence scanning interferometric microscopy) instruments] International Organization for Standardization, Geneva (2013).
[2] de Groot, P. J., "Coherence Scanning Interferometry," [Optical Measurement of Surface Topography], R. Leach, Ed., Berlin, Springer Verlag, (2011).
[3] Olympus Corporation, [3D Measuring Laser Microscope OLS4100], product brochure (2014).
[4] Keyence Corporation, [VK-X100/X200 series - 3D Laser Scanning Microscope], product brochure (2014).
[5] Sensofar Group, [S neox - 3D Optical Profiler], product brochure (2014).
[6] de Groot, P. J., "Progress in the specification of optical instruments for the measurement of surface form and texture," Proc. SPIE 9110, 91100M-1-12 (2014).

[7] U.S. Patent 3,971,065A, [Color imaging array], (1976).
[8] Hubel, P. M., Liu, J., Guttosch, R. J., “Spatial frequency response of color image sensors: Bayer color filters and Foveon X3,” Proc. SPIE 5301, (2004).
[9] Hubel, P. M., Bautsch, M., “Resolution for color photography,” Proc. SPIE 6069, (2006).
[10] Desse, J. M., Picart, P., Tankam, P., “Digital three-color holographic interferometry devoted to fluid mechanics,” Proc. SPIE 7387, (2010).
[11] Zygo Corporation, [Nexview(TM) Optical Profiler], Specification sheet SS-0095 09/12 (2013).
[12] U.S. Patent pending.