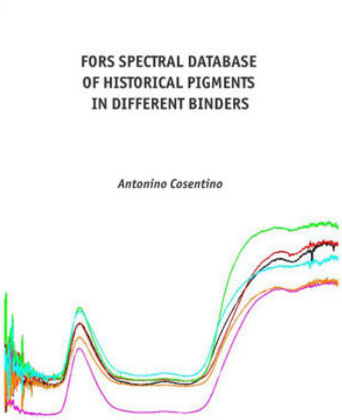

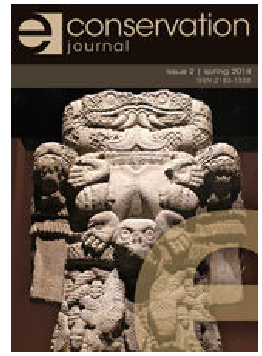

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Type II Super Lattice (T2SL) imaging technology for infrared reflectography of polychrome works of art

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Abstract
Artistic paints attenuate and diffuse infrared radiation less than visible light and thus infrared cameras can be used to inspect polychromed works of art for underdrawings and pentimenti. This paper discusses for the first time a Type II Super Lattice (T2SL) camera for infrared reflectography. A super lattice detector consists of a repeating sequence of very thin layers of different materials which creates sub-bands whose corresponding bandgap energies determine the cut-off wavelength of the sensor. First introduced in 1980s, T2SL technology is currently gaining interest for its imaging application in the SWIR (Short Wave Infrared) range over 1700 nm which is the longest radiation that an InGaAs camera can detect. InGaAs technology has replaced the vidicon tube, the first used for infrared reflectography. The Xenics Xeva T2SL camera is sensitive out to 2350 nm, as were the vidicon tubes, but with all of the significant advantages that come from a totally digital technology. This paper illustrates the use of this camera coupled with the panoramic method and a cut-off infrared filter and evaluates its performance against a collection of 54 swatches of historical pigments. The results are compared with the two, more common, infrared imagers currently used for art examination: an InGaAs camera and a modified full spectrum digital camera. The extended sensitivity of the camera above the 1700 nm limit of the InGaAs constitutes a sizable advantage because it takes advantage of the increased transparency of certain pigments, such as malachite, that have their maximum transparency at about 2000 nm.

1. Introduction

The examination and documentation of works of art and archaeological items is performed by a number of imaging methods. Some methodologies are routinely used in the art conservation field such as technical photography [1]: a collection of broadband spectral images usually made with a modified "full spectrum" digital camera (sensitivity between about 360 and 1100 nm), and different lighting sources and filters. Other imaging techniques are either more problematic or require more sophisticated equipment, such as multispectral imaging [2-4], and are primarily used on academic research. The use of infrared radiation for art examination is one of the oldest imaging method and it dates back to the 1930s when while photographing paintings with infrared film it was observed that the underdrawing lines were noticeable. Near infrared radiation is attenuated and diffused less than visible light when passing through paint layers [5-7]. Therefore, infrared cameras are primarily used to inspect a painting to attempt detecting the initial sketch drew before the artist painted it over with paint. The infrared image reveals the underdrawing due to the contrast between a ground layer that reflects the infrared and the drawing that absorbs it. An ideal example is represented by a gesso ground and a drawing created with a carbon-based ink or paint. Unfortunately, this is not always the case because the ground layer can be colored and/or the underdrawing could have been made with an infrared transparent pigment.

In general, pigments become more transparent as the wavelength of the incident light becomes longer. Therefore, a means to image paintings in the furthest infrared was sought. It was eventually discovered by R. J. van Asperen de Boer [8] who, in the 1960's, noticed that vidicon cameras, then used for TV broadcasting, had an extended sensitivity out to about 2000 nm. These detectors freed underdrawings from the paint hiding them. They took advantage of the increased transparency of pigments to reveal the painters' sketches almost as clearly as they were originally drawn. Only recently vidicon cameras have been replaced by InGaAs cameras, solid state FPA (focal plane array) imaging detectors covering the range 900-1700 nm [9]. Despite their shorter sensitivity, they are preferred over vidicon tubes which suffer from vignetting, an inherent feature that heavily affects the mosaicking process during the creation of IR reflectograms. The *full spectrum* modified digital photo cameras are sensitive to the infrared out to about 1100 nm. They are used by an increasing number of art conservators because some pigments become already transparent at that wavelength. These cameras are also popular because they are much more affordable than InGaAs imagers and because they provide a much higher pixel count, e.g. compare a 36 MP consumer digital camera that produces images of 7360x4912 pixels to a costly InGaAs camera which counts only 320 x 240 pixels. When using an infrared imager other than a full spectrum modified digital camera, in order to improve image resolution, some scanning systems must be used to either move the examined painting, the camera or just the detector inside the camera [10-12].

Infrared cameras are used in two experimental set ups. The simplest method detects the infrared light reflected from the surface of a painting illuminated by infrared lamps and with the camera facing the artwork. This method is called Infrared photography (IR) if performed with a full spectrum digital camera that operates in the NIR (near infrared) region or infrared reflectography (IRR) if detectors sensitive to the SWIR (short wave infrared) range, over 1100 nm, such as the Vidicon or InGaAs cameras, are used. In the case of works of art on translucent media, the infrared radiation can come also from the back and the method is called transmitted infrared (IRT) or transmitted infrared reflectography (IRRT). For paintings on canvas, the transmitted method can often reveal much more information than the reflected infrared one [13]. Another infrared imaging method uses a source of visible light to excite infrared fluorescence (IRF) [14-16] while infrared false color (IRFC), once made with dedicated film [17], is now made with the same full spectrum digital cameras [18].

After the promising first results achieved with the infrared photography film, almost as soon as a new infrared imaging sensor has been made available, it is tested for inspection of works of art: infrared image-converter [19], vidicon tube [8], PtSi [20], CCD [21], InGaAs, HgCdTe, and InSb detectors [9].

This paper discusses for the first time a Type II Super Lattice (T2SL) infrared camera for the examination of polychromed works of art. First proposed in 1980s [22-25], T2SL technology has gained interest for infrared detection applications in the SWIR (Short Wave Infrared) range over the 1700 nm limit achieved with the InGaAs cameras. Currently, commercial technologies for the SWIR range are based on indium antimonide (InSb), mercury cadmium telluride (HgCdTe or MCT) although these materials are fundamentally limited by Auger recombination (one of the main dark current components), which is a limiting factor for high-temperature operation. A super lattice is a repeating sequence of thin layers of different materials whose thicknesses are accurately chosen in order to create sub-bands and corresponding bandgap energies to allow the detection of photons of the desired wavelength. The super lattice of these infrared cameras is formed by multiple periods of alternating thin InAs and GaSb layers.

This paper illustrates the use of this T2SL camera for the examination of polychrome works of art and coupled with the panoramic method and a cut off infrared filter. The features of this camera are compared with the two more common infrared imagers used for art examination: an InGaAs camera and a modified full spectrum digital camera.

2. Experimental

Three infrared imagers were used for this study: a) a "full spectrum" modified DSLR Nikon D800 digital camera, equipped with a CMOS sensor that responds to both the near infrared and near ultraviolet ranges of the spectrum (approximately the 360-1100 nm range), and equipped with a Heliopan RG 1000 filter [26] for infrared photography; b) Xenics Bobcat-640-GigE, a 640x512 pixels InGaAs camera [27], sensitive from 900 to 1700 nm; and c) Xenics Xeva-2.35-320 TE4, a 320x256 pixels T2SL (Type II Super Lattice) camera, sensitive from 1000 to 2350 nm (Figure 1). This camera allows for exposure times from 1 μs to more than 100 ms in high dynamic range mode (with TE4 cooling device operating down to 220K).

The cameras have been tested on the "pigments' checker", a collection of 54 swatches of historical pigments applied with gum arabic as binder on a cellulose and cotton watercolor paper, acids and lignin free (Fabriano, Torchon 270g/m^2). Two cross-hair lines, 0.2 mm (vertical) and 0.4 mm (horizontal), were printed on each swatch of paper before the application of paint, in order to have a way to evaluate the pigment transparency in the IR and IRR imaging. The pigments were mulled into the binder, added as needed for each pigment and applied with a brush. No other means to control and measure thickness of the paint and binder-pigment ratio were implemented. The pigments are commercially available from Kremer Pigments and information regarding their composition and manufacturing processes is available on the company website using their respective product code. Table I shows the name and product code of each pigment.

Table I. Distribution by color of the 54 historical pigments (Kremer Pigments) studied in this paper and respective product code.

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http://e-conservation.org/104-T2SL-for-infrared-reflectography#sigFreeId57e57a4762

The capacity of the different cameras to penetrate paints of varying thickness was evaluated on a board, hereafter referred to as the "thickness test panel", composed of the same watercolor paper that was first printed with 3 lines of different width: 0.3, 0.7 and 1 mm (Figure 2). The lines were then fixed with dammar resin (Easy, 69.303.125) and three paint layers were applied using gum arabic as binder: vermilion, raw sienna and malachite. The same procedure as for the pigments' checker was used to layout and prepare the paints. The paints were fixed with an acrylic resin (Maimeri # 675) and a second paint layer was added on two thirds of each swatch. The procedure was repeated to add another third paint layer on one third of each swatch.

Another pigment board referred to as "pigments checker canvas" was prepared to evaluate the cameras for the infrared transmittance method. The canvas used was a cotton/polyester fine grain fabric of 320gr/m^2 with a titanium white and acrylic resin ground (ref. 569, pieraccini.com) (Figure 3). Two 0.4 mm cross-hair lines (horizontal and vertical) were drawn on the canvas before the application of paint in order to have a means to evaluate the pigment transparency in the infrared. The lines were then fixed with an acrylic resin (Maimeri #675). Eventually, the canvas was covered with a matte cardboard printed with the pigments names and codes.

The InGaAs and T2SL cameras were coupled to a Gigapan Epic Pro panoramic head in order to acquire the reflectograms with the panoramic infrared reflectography method [27].

Left to right:
Figure 1. Xenics Xeva-2.35-320 TE4, a 320x256 pixels T2SL camera coupled with a panoramic head imaging the pigments' checker.
Figure 2. Thickness test panel: a) the printed cardboard; b) the board prepared with 3 overlapped layers of paints for each pigment (from left to right) malachite, raw sienna and vermilion; c) cross-sections of the thickest sections of the 3 swatches.
Figure 3. Pigments checker canvas: a) canvas and printed card board mask with the pigments' names and codes; b) photo with the cardboard mask; c) transmitted infrared reflectography (InGaAs camera); d) transmitted infrared reflectography (InGaAs camera with Thorlabs FEL 1500 filter).

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3. Results and Discussion

The T2SL infrared camera was first tested on the pigments checker and the resulting image compared with that acquired with the CMOS digital camera and the InGaAs camera (Figure 4). The CMOS images were acquired with just one shot (spatial resolution 20 pixels/mm) using a Nikon Nikkor 50mm AF 1.8 D. The InGaAs image was created by stitching 20 images (spatial resolution 6 pixels/mm) and using a Nikon Nikkor 200mm f4 AI. The T2SL image was acquired with the same lens but stitching 36 images (since the T2SL camera has a lower pixels count).

As expected, the pigments become more transparent in the InGaAs and T2SL images than in the CMOS, and no apparent advantage was noted among the InGaAs and T2SL. The increased sensitivity of the T2SL camera out to 2350 nm does not appear to provide any noticeable increase in transparency comparatively across the 52 pigments.

To take full advantage of the extended sensitivity of the T2SL camera, it is necessary to add an infrared filter such as the Thorlabs FEL 1500 which cuts off radiation below 1500 nm and transmits until 2500 nm. With this filter, the T2SL camera was tested on the thickness test panel. The three pigments (malachite, raw sienna and vermilion) have specifically been chosen based on their characteristic spectral hiding thickness [8] which represents for each wavelength the minimum thickness of a paint that makes it opaque. These three pigments summarize the characteristic behavior of the hiding thickness of the 52 historical pigments tested at the infrared range from 1000 to 2350 nm.

The hiding thickness of malachite gradually increases over the infrared wavelengths to which the T2SL camera is sensitive and reaches its maximum at about 2000 nm. This pigment is very opaque at shorter infrared wavelength (CMOS) (Figure 5), and just becomes transparent at the longest infrared wavelengths provided by InGaAs and T2SL cameras. The InGaAs camera can successfully detect the underlines in the test panel only if the 1500 nm cut-off filter is used (Figure 6). The lines under the first layer of paint then become visible. The same is observed for the T2SL camera, without a filter the underlines cannot effectively be detected. However, once filtered it provides a sharper image of the lines than the InGaAs one thanks to the increased transparency of malachite in the extended infrared range reached by the T2SL camera. The extended sensitivity of the T2SL camera is essential to produce images of the underdrawing under the malachite paint. Even so, malachite is very opaque and only the lines under one paint layer can be resolved even with the T2SL camera.

Left to right:
Figure 4. Pigments checker, a collection of 54 historical pigments, tested with three infrared cameras.
Figure 5. Thickness test panel examined with three infrared cameras with and without a cut-off infrared filter.

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The spectral hiding thickness of raw sienna reaches its maximum also around 2000 nm but it is already high at short infrared wavelengths and the paint is by then transparent using an InGaAs camera without filter. The lines are visible under all the three layers of raw sienna paint. While the lines can be resolved with the InGaAs camera, they become sharper with the T2SL filtered camera (Figure 5).

Vermilion features an almost flat spectral hiding thickness across the infrared range which just slightly increases over the longer infrared wavelengths. Consequently, the vermilion paint remains opaque and it does not reveal any under line with any of the cameras, even filtered (Figure 5).

The advantage of using a filter on an infrared reflectography camera was tested also for the transmitted infrared reflectography method using the “pigments checker canvas”. The filter allows to increase the reading of underlines in transmitted infrared for pigments such as malachite, azurite and green earth whose hiding power increases at longer infrared wavelengths (Figure 7).

Left to right:
Figure 6. Thickness test panel, detail of the malachite swatch and gray values plots of the infrared images taken with and without the Thorlabs FEL 1500 filter. The curves show the gray values corresponding the yellow dotted line.
Figure 7. Pigments checker canvas, detail of the transmitted infrared reflectography of azurite, malachite and green earth swatches with and without 1500 cut-off filter.

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4. Conclusions

The extended sensitivity of the T2SL camera constitutes a sizable advantage over traditional InGaAs cameras. The InGaAs technology is fully developed and these cameras feature detectors with larger pixel counts compared to current T2SL cameras. This is valuable feature for the panoramic infrared reflectography method in order to guarantee faster stitching, more precision and higher resolution. Furthermore, InGaAs cameras can operate at high temperature and consequently they are very lightweight and compact since they do not need bulky cooling systems. On the other hand, the extended sensitivity of the T2SL camera over the 1700 nm limit of the InGaAs allows to take advantage of the increased transparency of some pigments such as malachite that have their maximum transparency at about 2000 nm. T2SL technology is therefore very promising as a possible substitute of InGaAs cameras for more performant infrared reflectography of works of art.

5. Acknowledgments

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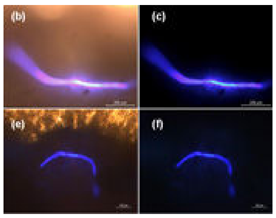

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