

HYPERSPECTRAL IMAGING DEVICE

FIELD OF THE INVENTION

[0001] This invention relates to imaging devices, more particular to improved imaging devices which create interference fringes.

BACKGROUND OF THE INVENTION

[0002] Polarisers are devices which absorb all the components of an electromagnetic field in one direction while allowing components in a perpendicular direction to pass through. Polarisers are used in Savart polariscopes which can be used to generate interference fringes. Savart polariscopes comprise a polariser and an analyzer with a pair of birefringent layers positioned between the polariser and the analyzer. The first birefringent layer has an optic axis which is at a 45° angle with respect to an optical axis of light. The second birefringent layer has a second optic axis which is at a 45° angle in a plane at right angles to a plane containing the first optic axis. The Savart polariscope takes polarised light and, after passing through the birefringent layers, the analyzer and a lens, generates an interferogram of a series of fringes. The interferogram can be subjected to computational analysis which is in turn used for comparison with reference spectrum.

[0003] Savart polariscopes have seen limited adoption because the fringes produced are generally sharply curved (hyperbolas, conoscopic shapes, etc.) in a standard field of view of a camera, are not evenly spaced and/or include secondary fringes.

1 This makes the fringes difficult to process to obtain accurate information with
2 excessive computational complexity.

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4 [0004] A modified Savart polariscope uses a half-wave plate inserted between the
5 two birefringent layers. A half-wave plate is another birefringent layer. Use of the
6 half-wave plate has the benefit of generating relatively linear fringes in a standard
7 field of view, and therefore allows for more efficient processing of interferograms.
8 However, this modification still has significant drawbacks, as a particular half-wave
9 plate is typically limited to a specified narrow range of wavelengths. Further half-
10 wave plates which are achromatic, i.e., work over a wide range of wavelengths, are
11 relatively expensive and may still require an undesirably large field of view in the
12 camera which receives the interferogram to be processed.

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14 [0005] It would therefore be desirable to provide a device capable of generating an
15 interferogram of interference fringes that are easy to analyze, which is of low cost
16 and is relatively easy to manufacture.

17 18 SUMMARY OF THE INVENTION

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20 [0006] In accordance with a first aspect, there is provided an imaging device for
21 processing light comprising a polariser defining an X-Y plane having an X-axis and a
22 Y-axis, wherein an optical axis extends along a Z-axis perpendicular to the X-Y
23 plane. The polariser is adapted to transmit light linearly polarised at a polarisation
24 angle formed in the X-Y plane. A first birefringent layer having a first optic axis at a
25 first angle formed in an X-Z plane formed by the X-axis and the Z-axis, and a second

1 birefringent layer having an second optic axis formed at a second angle. An
2 analyzer adapted to transmit light from the second birefringent layer to a camera.
3 The light so transmitted is linearly polarised at an analyzer angle formed in the X-Y
4 plane. The device has only two birefringent layers, and the light transmitted to the
5 camera forms linear fringes.

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7 [0007] From the foregoing disclosure and the following more detailed description of
8 various embodiments it will be apparent to those skilled in the art that the present
9 invention provides a significant advance in the technology of imaging devices.
10 Particularly significant in this regard is the potential the invention affords for providing
11 a high quality imaging device for producing interference fringes. Additional features
12 and advantages of various embodiments will be better understood in view of the
13 detailed description provided below.

14 BRIEF DESCRIPTION OF THE DRAWINGS

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17 [0008] Fig. 1 is an isometric view of an imaging device in accordance with one
18 embodiment.

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20 [0009] Fig. 2 depicts a schematic optical layout of the imaging device in accordance
21 with one embodiment illustrating the path of light through two birefringent layers.

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23 [0010] Fig. 3 depicts a schematic optical layout of another embodiment of the
24 imaging device.

1 [0011] Fig. 4 illustrates a spectrum corresponding to a processed image.

3 [0012] Fig. 5 illustrates a reference spectrum.

5 [0013] Fig. 6 depicts a schematic example of the spaced fringes generated at a field
6 of view of the camera.

8 [0014] Fig. 7 represents a schematic interferogram generated by the imaging device.

10 [0015] It should be understood that the appended drawings are not necessarily to
11 scale, presenting a somewhat simplified representation of various features illustrative
12 of the basic principles of the invention. The specific design features of the imaging
13 device as disclosed here, including, for example, the specific dimensions of the
14 birefringent layers, will be determined in part by the particular intended application
15 and use environment. Certain features of the illustrated embodiments have been
16 enlarged or distorted relative to others to help provide clear understanding. In
17 particular, thin features may be thickened, for example, for clarity of illustration. All
18 references to direction and position, unless otherwise indicated, refer to the
19 orientation illustrated in the drawings.

21 DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

23 [0016] It will be apparent to those skilled in the art, that is, to those who have
24 knowledge or experience in this area of technology, that many uses and design
25 variations are possible for the imaging device disclosed here. The following detailed

discussion of various alternate features and embodiments will illustrate the general principles of the invention with reference to an imaging device suitable for use as a hyperspectral imaging device. Other embodiments suitable for other applications such as environmental monitoring of chemicals and pollutants, satellite imaging, search and rescue missions, monitoring of crops, mineralogy identification such as oil fields, vision for industrial automation, medical imaging and forensic applications, will be apparent to those skilled in the art given the benefit of this disclosure.

[0017] Turning now to the drawings, Fig. 1 is an isometric view of an imaging device 10 in accordance with one embodiment suitable for use as a hyperspectral imaging device. Advantageously, as shown the device 10 is compact and lightweight with a small footprint and a subassembly can be assembled within a housing of the camera.

[0018] Fig. 2 shows a schematic optical layout of an embodiment of the device. Light from an outside source has an optical axis which extends along the Z-axis, which is a horizontal axis in the plane of the paper as shown in Fig. 2. The light passes through a polariser 20 which has a polarisation angle 21. The polarisation angle 21 is shown to be formed in an X-Y plane. The X-Y plane is generally perpendicular to the Z-axis as shown in Fig. 2. The polariser transmits light linearly polarised at the polarization angle in the X-Y plane. In accordance with one embodiment, the polariser angle may be 45° with respect to the X-axis. The light passes through the polariser is a linearly polarised beam which is transmitted to a first birefringent layer 22 having a first optic axis 23 formed at a first angle, then to a second birefringent layer 24 having a second optic axis 29 formed at a second angle, then to an analyzer

26, then to a lens 28 which focuses the light onto a field of view of a charge coupling device of a digital camera 30. The analyzer 26 has an analyzer angle 31 which is related to the polariser angle 21. Generally, the analyzer angle is either the same as the polariser angle with respect to the X-axis or at a 90° angle with respect to the polariser angle. For example, the polariser angle 21 can be 45° with respect to the X-axis and the analyzer angle 31 may be either $\pm 45^\circ$ with respect to the X-axis.

[0019] After passing through the polariser 20, the linearly polarised light passes through the first birefringent layer 22, causing the light to be sheared laterally into two virtual sources that are orthogonal components of the polarised light. These components are sometimes referred to as the extraordinary ray or e-ray and ordinary ray or o-ray. The e-ray and the o-ray have different refractive indices. Consequently, one ray travels faster than the other through the layer 22 resulting in a phase difference between the e-ray and o-ray. The resulting phase difference is a function of several properties of the layer 22 and the light, including the propagation direction of e-ray and o-ray within the layer 22, a cut angle of the layer 22 with respect to the first optic axis 23, an angle between a plane containing the optic axis 23 and a plane of incidence of the light, a wavelength of the polarised light, a thickness 25 of the layer and a material of layer 22.

[0020] The first birefringent layer is positioned between the polariser and the second birefringent layer such that the e-ray and o-ray exit the first birefringent layer 22 and immediately enter the second birefringent layer 24. Preferably the birefringent layers 22, 24 are in direct contact with one another as shown in the embodiments of the Figs. The second birefringent layer 26 has a second angle 29 which is related to the

first angle 23. In the embodiments represented by Fig. 2, the second birefringent layer 24 compensates for the phase difference generated by the first birefringent layer by having a slow axis of the second birefringent layer orthogonal to a slow axis of the first birefringent layer. The amount of phase difference compensated in the second birefringent layer is a function of several properties of the layer 24 and the light, including the propagation direction of e-ray and o-ray within the layer 24, a cut angle of the layer 24 with respect to the optic axis 129, a wavelength of the polarised light, a thickness 27 of the layer and a material of layer 24.

[0021] In accordance with a highly advantageous feature, only two birefringent layers are used to generate linear fringes. The optic axis 23 of the first birefringent layer 22 lies at an angle from the X-axis in an X-Z plane, where the X-Z plane is defined by the X-axis and the Z-axis. Optionally the first angle is 30-60° from the X-axis, and more preferably at +45° from the X-axis, since this angle is associated with generation of fringes requiring reduced computational processing. In this embodiment, the optic axis 29 of the second birefringent layer 24 is within $\pm 10^\circ$ of the Y-axis, and more preferably perpendicular to the Z-axis and along the Y-axis. This can also be expressed as at a 90° angle with respect to the X-axis or Z-axis. In these embodiments the second angle 29 is in a plane orthogonal to the first angle 23. Again, a first angle of 45° and a second angle of 90° is associated with generation of fringes requiring reduced computational processing. In this embodiment, both layers have positive birefringence, such that the velocity of the ordinary ray is greater than that of the extraordinary ray. Although a first angle of 45° and a second angle of 90° is recited in this embodiment, a similar result can be achieved with other angles by adjusting thicknesses 25, 27 or material selection of

the layers 22, 24 respectively. Also in this embodiment, upon exiting the first birefringent layer, the sheared polarised beams enters the second birefringent layer. The e-ray in the first birefringent layer becomes an o-ray in the second birefringent layer. Likewise, the o-ray in the first birefringent layer becomes an e-ray in the second birefringent layer. In this embodiment, the thickness 25 of the positive first birefringent layer 22 is larger than the thickness 27 of the positive second birefringent layer 24 and both crystals are optionally made of the same material.

[0022] The embodiment described above can be varied by adjusting the first angle or the birefringence of the first layer, but if the birefringence is adjusted, then the birefringence of the second layer must be adjusted as well. For example, a positive first birefringent layer 22 has an optic axis lying in the X-Z plane at -45° from the X-axis. The corresponding second birefringent layer 24 has the same second angle as described in the paragraph immediately above, and has positive birefringence. For either first angle, if the birefringence of the first layer 22 is switched to negative birefringence then the birefringence of the second layer 24 is similarly switched to negative. Both layers have the same birefringence merely in the sense that both are either positive or negative. In each of these embodiments, the second thickness 27 is less than the first thickness 25.

[0023] Fig. 3 illustrates a schematic of optical layout of another embodiment where the first birefringent layer 22 and the second birefringent layer 124 are of different materials. The layers 22, 124 have opposite birefringence merely in the sense that when one is positive the other is negative. The optic axis of the first birefringent layer 22 lies in the X-Z plane and the optic axis of the second birefringent layer 124

lies in the X-Z plane as well. The first angle may be the same as the second angle with respect to the X-axis. The first layer 22 has positive birefringence and the second layer 124 has negative birefringence. Optionally the first angle 23 is at $\pm 45^\circ$ from the X-axis and the second angle 129 is independently at $\pm 45^\circ$ from the X-axis as well. The second angle can be, for example, an angle equal in magnitude and opposite to the first angle with respect to the X-axis, such as -45° when the first angle is $+45^\circ$. Also, the birefringence of the layers may be switched such that the first layer 22 has negative birefringence and the second layer 124 has positive birefringence. Since the layers 22, 124 comprise different materials, a chirp is introduced in the resulting signal. The chirp advantageously helps reduce a dynamic range required to improve signal-to-noise ratio.

[0024] As with the embodiments of Fig. 2, the linearly polarised beam from the polariser enters the first birefringent layer 22 and is laterally sheared into two virtual components – the o-ray and the e-ray. Upon exiting the first birefringent layer, the e-ray and the o-ray enter the second birefringent layer 124. With the embodiments of Fig. 3 which have opposite birefringence, the e-ray in the first birefringent layer remains an e-ray in the second birefringent layer. Likewise, the o-ray in the first birefringent layer remains an o-ray in the second birefringent layer. In all of the above embodiments, upon exiting the second birefringent layer, there will be a net phase difference between the laterally sheared e-ray and the o-ray.

[0025] From any of the embodiments, the two beams with a net phase difference exit the second birefringent layer and pass through the analyzer 26. The analyzer 26 is used to make the exiting e-ray and o-ray polarised beams interfere. Alternating

1 bright and dark intensities are fringes which are captured by the CCD (camera) 30 as
2 a raw image upon focusing of light received from the analyzer by the focusing lens
3 28. See Fig. 6. The generated fringes will be superimposed onto the image of the
4 outside source or scene captured by the CCD. In accordance with a highly
5 advantageous feature, use of the optics of the subassembly (polariser, first
6 birefringent layer, second birefringent layer and analyzer) as disclosed herein
7 produces fringes which are generally linear and evenly spaced. It will be readily
8 apparent to those skilled in the art given the benefit of this disclosure, that linear here
9 means generally linear or parallel and not a perfect mathematical relationship, and
10 that generally evenly spaced apart fringes are generally equidistantly spaced apart
11 but not necessarily perfectly consistently spaced apart. Such linear, evenly spaced
12 fringes are advantageously much easier to process into useful spectrum data than
13 the nonlinear, unevenly spaced hyperbolic or conoscopic fringes generated by some
14 known technologies.

15
16 [0026] An interferogram for a point is built up from the intensity values of that point
17 taken from each and every image captured by the device. Fig. 7 shows a
18 representative plot of an interferogram with intensity of light on the Y-axis and an
19 angle range along the X-axis. This would be the case where at least the
20 subassembly is rotated with respect to the outside source or scene. The
21 interferogram may also be generated by generating a sequence of fringes over a
22 period of time. Rotation may occur by use of a motor (not shown) operable to move
23 at least the subassembly. The intensity value of a point fluctuates as the fringes
24 shifts with respect to the point. A processor can be used to process the raw image
25 of spectral information into a processed image by use of Fourier transforms, for

1 example. The processed image has a range of wavelengths (Fig. 4) which can be
2 compared with a reference spectrum (Fig. 5) to identify the range of wavelengths of
3 the processed image. Alternatively, the processor has access to a reference
4 spectrum (Fig. 5) with a range of wavelengths and at least one of a range of
5 wavelengths can be selected by a user of the device, and the device can scan a
6 source for the selected range of wavelengths.

7
8 [0027] From the foregoing disclosure and detailed description of certain
9 embodiments, it will be apparent that various modifications, additions and other
10 alternative embodiments are possible without departing from the true scope and
11 spirit of the invention. The embodiments discussed were chosen and described to
12 provide the best illustration of the principles of the invention and its practical
13 application to thereby enable one of ordinary skill in the art to use the invention in
14 various embodiments and with various modifications as are suited to the particular
15 use contemplated. All such modifications and variations are within the scope of the
16 invention as determined by the appended claims when interpreted in accordance
17 with the breadth to which they are fairly, legally, and equitably entitled.

CLAIMS

What is claimed is:

1. An imaging device for processing light, comprising, in combination:
 - a polariser defining an X-Y plane having an X-axis and a Y-axis, wherein an optical axis extends along a Z-axis perpendicular to the X-Y plane, and the polariser is adapted to transmit light linearly polarised at a polarisation angle formed in the X-Y plane;
 - a first birefringent layer having one of positive birefringence and negative birefringence and having a first optic axis at a first angle formed in an X-Z plane formed by the X-axis and the Z-axis;
 - a second birefringent layer having a second optic axis formed at a second angle, wherein the second angle is one of within $\pm 10^\circ$ of the Y-axis and an angle formed in the X-Z plane; and
 - an analyzer adapted to transmit light from the second birefringent layer to a camera, wherein the light so transmitted is linearly polarised at an analyzer angle formed in the X-Y plane;
- wherein the device has only two birefringent layers, and when the second angle is formed in the X-Z plane, then the second birefringent layer has a birefringence opposite the first birefringent layer.
2. The imaging device of claim 1 wherein the second angle is within $\pm 10^\circ$ of the Y-axis and the first birefringent layer has one of positive birefringence and negative birefringence, and the second birefringent layer has the same birefringence as the first birefringent layer.

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2 3. The imaging device of claim 1, wherein the second angle is within $\pm 10^\circ$ of the
3 Y-axis and the first birefringent layer has a first thickness, the second birefringent
4 layer has a second thickness, and the second thickness is less than the first
5 thickness.

6
7 4. An imaging device for processing light, comprising, in combination:
8 a polariser defining an X-Y plane having an X-axis and a Y-axis, wherein an
9 optical axis extends along a Z-axis perpendicular to the X-Y plane and an X-Z plane,
10 and the polariser is adapted to transmit light linearly polarised at a polarisation angle
11 formed in the X-Y plane;
12 a first birefringent layer having an first optic axis at a first angle;
13 a second birefringent layer having an second optic axis formed at a second
14 angle; and
15 an analyzer adapted to transmit light from the second birefringent layer to a
16 camera, wherein the light so transmitted is linearly polarised at an analyzer angle
17 formed in the X-Y plane;
18 wherein the device has only two birefringent layers, and the light transmitted
19 to the camera forms linear fringes.

20
21 5. The imaging device of claim 1 or claim 4 wherein the polarisation angle is 45
22 degrees with respect to the X-axis and the analyzer angle is 45 degrees with respect
23 to the X-axis.

6. The imaging device of claim 1 or claim 4 wherein the analyzer angle is at one of the same as the polariser angle with respect to the X-axis and at 90° with respect to the polariser angle.

7. The imaging device of claims 1 or 4 wherein the first angle is 30-60° from the X-axis.

8. The imaging device of claims 7 wherein the first angle is 45° from the X-axis.

9. The imaging device of claims 1 or 4 wherein the second angle is formed in the X-Z plane and is at one of the same angle as the first angle with respect to the X-axis and an angle equal in magnitude and opposite to the first angle with respect to the X-axis.

10. The imaging device of claims 1 and 4 further comprising a focusing lens positioned between the analyzer and the camera, wherein the focusing lens focuses light received from the analyzer on the camera.

11. The imaging device of claims 1 and 4 wherein the first birefringent layer and the second birefringent layer are in direct contact with one another.

12. The imaging device of claims 1 and 4 wherein the first birefringent layer is positioned between the polariser and the second birefringent layer.

1 13. The imaging device of claims 1 and 4 wherein light passing from the polariser
2 to the camera produces a raw image, and further comprising a processor which
3 processes the raw image into a processed image.

4
5 14. The imaging device of claim 13 wherein the processed image has a range of
6 wavelengths which can be compared with a reference spectrum to identify the range
7 of wavelengths of the processed image.

8
9 15. The imaging device of claim 13 wherein the processor has access to a
10 reference spectrum with a range of wavelengths, at least one of a range of
11 wavelengths can be selected, and the device can scan for the selected range of
12 wavelengths.

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14 16. The imaging device of claim 1 wherein light received by the camera forms
15 linear fringes.

16
17 17. The imaging device of claims 4 and 16 wherein the fringes are evenly spaced.

18
19 18. The imaging device of claims 1 and 4 wherein the second angle is formed at
20 90° from the Z-axis along the Y-axis.

21
22 19. The imaging device of claims 1 and 4 wherein the polariser, first birefringent
23 layer, second birefringent layer, and analyzer comprise a subassembly, and further
24 comprising a motor operable to move the subassembly.