A method and apparatus for modulating a light beam in an optical processing system is described. Preferably, an electrically-controlled polarizer unit and/or an analyzer unit are utilized in combination with a spatial light modulator and a controller. Preferably, the spatial light modulator comprises a pixelated birefringent medium such as a liquid crystal video display. The combination of the electrically controlled polarizer unit and analyzer unit make it simple and fast to reconfigure the modulation described by the Jones matrix of the spatial light modulator. A particular optical processing objective is provided to the controller. The controller performs calculations and supplies control signals to the polarizer unit, the analyzer unit, and the spatial light modulator in order to obtain the optical processing objective.
FIG. 5C
FIG. 5F
DIGITIZE INPUT IMAGE
(OBJECT OF INTEREST)

CALCULATE DIGITAL
FOURIER TRANSFORM
(COMPLEX VALUE)

REPRESENT THE COMPLEX
VALUES DESIRED AS BEST
POSSIBLE WITH THOSE
ACHIEVABLE USING FIRST
OPERATING CURVE

STORE FILTER VALUES
AND THE DIGITAL WORD
WHICH PRODUCES THE
OPERATING CURVE

CALCULATE METRIC
OF INTEREST, i.e.,
CORRELATION PEAK
HEIGHT, SIGNAL-TO-NOISE
RATIO, etc.

FIG. 6A
REPRESENT THE COMPLEX VALUES DESIRED AS BEST POSSIBLE WITH THOSE ACHIEVABLE USING THE NEXT OPERATING CURVE

CALCULATE METRIC OF INTEREST, i.e., CORRELATION PEAK HEIGHT, SIGNAL-TO-NOISE RATIO, etc.

IS THE VALUE OF THE METRIC GREATER THAN THE PREVIOUS VALUE?

STORE FILTER VALUES AND THE DIGITAL WORD WHICH PRODUCES THE OPERATING CURVE

FIG. 6B
METHOD AND APPARATUS FOR IMPROVED SPATIAL LIGHT MODULATION

This is a division of application Ser. No. 08/327,762, filed Oct. 24, 1994, now U.S. Pat. No. 5,859,728.

ORIGIN OF THE INVENTION

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

The present invention relates in general to optical processing systems, and in particular to an improved method and apparatus for modulating a light beam in an optical processing system.

1. Field of the Invention

The present invention relates more particularly to optical processing systems that utilize spatial light modulators to encode and/or filter information onto or from a light beam, typically a coherent laser beam. These spatial light modulators operate by modulating a light beam in two dimensions by changing the intensity and/or phase of the light wave in a controllable manner. Thus, they can be used to introduce spatial patterns onto a light beam. The commercially available spatial light modulators however tend to be expensive. As a consequence, many optical processing systems utilize liquid crystal video displays as an inexpensive and readily available alternative to spatial light modulators. They may be obtained from commercially-available color video projector units, such as the Crystal Image Video Projector unit Model No. E1020, manufactured by Epson. Such projector units have a reasonable optical quality insofar as they are spatially uniform. Furthermore, each liquid crystal display is individually electrically addressable. The displays are typically driven utilizing a specialized electronic drive circuit which is supplied with the projector unit. The drive circuit acts as an interface between an analog video signal and the two dimensional matrix of pixels which make up the liquid crystal video display at that particular pixel. The voltage across each pixel of the liquid crystal video display is proportional to the gray scale level at the corresponding location in the video display. Typically, the liquid crystal video displays are twisted-nematic liquid crystal devices, which means that the optical birefringent axes, caused by the anisotropy of the liquid crystal molecules, rotate throughout the thickness of the cell, in a manner similar to that depicted in FIG. 1A. The birefringence is altered or modulated by the application of the drive voltage (which is derived from the video signal) across a pixel. This change in the birefringence causes a change in the polarization state of any light beams which pass through the liquid crystal video display. If the liquid crystal video display is disposed between two polarizing optical instruments, the polarization modulation is converted to amplitude or phase modulation of the light beam. It is the amplitude and/or phase modulation of a light beam which allows for the processing of images. More specifically, the amplitude and/or phase modulation can be utilized for either encoding information onto the light beam, or for filtering or otherwise manipulating information on the light beam. Since the interaction between the light beam and the liquid crystal video display is fairly complicated, a simple amplitude-only modulation or phase-only modulation is not possible.

The liquid crystal video displays are merely one type of "complex spatial light modulator" which are utilized in optical processing systems. A complex spatial light modulator can be characterized as an optical processing device whose action on a light beam may be expressed as affecting the phase and amplitude (or alternately, the real and imaginary parts) of an incident light beam. Typically, spatial light modulators such as the liquid crystal video display, are useful for optical processing of images as a function of position over the active area of the optical processing device. While liquid crystal displays may be electrically addressed on a pixel-by-pixel basis, other types of complex spatial light modulators are addressable as a continuous function of position. For purposes of the present application, the terms "complex spatial light modulator" and "spatial light modulator" will define all optical devices which affect the phase and amplitude of an incident light beam; however, the preferred embodiment discussed herein will specifically refer to a liquid crystal video display, which is merely one type of complex spatial light modulator.

The prior art devices used for generating and analyzing specific polarization states include one device developed by J. L. Pezzaniti and R. A. Chipman which permits the automated measurement of the Mueller matrix of a spatial light modulator. This device is described in detail in the following publications:

J. L. Pezzaniti and R. A. Chipman, "Phase-only Modulation Of A Twisted Nematic Liquid-Crystal TV By Use Of The Eigenpolarization States", Optics Letters vol. 18, pp. 1567–1569 (September 1993); and


A major distinction of the present invention from the Pezzaniti and Chipman device is that the Pezzaniti and Chipman device requires gross physical motion (rotation) of polarizers and retarders in order to generate and analyze its set of polarization states. Another distinction of the present invention is its preferred embodiment as a laboratory bench tool to characterize the polarization properties of spatial light modulators, as opposed to the present invention's major operational intent of providing immediate access to any of a plurality of different polarization behaviors. Accordingly, its slower, more accurate, more stable, bulkier, heavier, more complicated, and more precise that the present invention.

SUMMARY OF THE INVENTION

It is one objective of the present invention to utilize the rather large number of different operating characteristics which are possible with complex spatial light modulators in order to achieve particular optical processing objectives.

Still more particularly, it is another objective of the present invention to utilize a complex spatial light modulator in combination with at least one of (1) a polarizer unit, and (2) an analyzer unit, which has an optical effect on the light beam, which either is incident to the complex spatial light modulator or emergent from the complex spatial light modulator, in a manner which is determined by one or more electrical control signals provided by a controller.

It is a still more particular objective of the present invention to utilize the controller in order to respond to a provided optical processing objective by examining a predetermined number of optical transform options available...
through the control parameters which may be provided to
one or more of the complex spatial light modulator, a
polarizer unit, and an analyzer unit.

These and other objectives are achieved as is now
described. The present invention may be characterized as
either a method or apparatus for processing a light beam. At
least one of a polarizer unit and an analyzer unit are
provided. The polarizer unit polarizes an incident light beam
in a selected one of a plurality of available polarization states
in response to receipt of at least a selected one of a plurality
of available electrical command signals. The analyzer unit
selects from an incident light beam one of a plurality of
available polarization states in response to receipt of at least
a selected one of a plurality of available electrical command signals. A spatial light modulator is provided for receiving
an incident light beam and modulating the incident light beam
by converting one polarization state into another in
accordance with an optical polarization transform associated
with an operating range of at least one drive parameter for
the spatial light modulator. Additionally, a controller member
is provided for supplying control signals to at least one of
the polarizer unit and the analyzer unit. A particular optical processing
objective is provided to the controller member, and the
controller member utilizes to supply the control signals to
at least one of the polarizer unit and the analyzer unit, and
to supply at least one drive parameter value to the spatial
light modulator, in a manner which obtains or achieves the
optical processing objective.

Additional objectives, features and advantages will be
apparent in the written description which follows.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are
set forth in the appended claims. The invention itself,
however, as well as a preferred mode of use, further objectives
and advantages thereof, will best be understood by
reference to the following detailed description of an illustrative
embodiment when read in conjunction with the accompanying
drawings, wherein:

FIG. 1A depicts the changing direction of the extraordinary
birefringent axis of light through the thickness of an
LCD screen;

FIG. 1B is a block diagram of light propagating through
linear optical elements including their Jones matrices;

FIGS. 2A–2C each is a graph of selectable operating
curves according to the present invention;

FIG. 2D is a graph of hypothetical ideal complex filter
values according to the present invention, in which it is seen
that the ideal values (dots) conform more closely to the
curve of FIG. 2A than to either of the others;

FIG. 3 depicts a block diagram of a spatial light modulator
according to the present invention;

FIGS. 4A and 4B depict a block diagram of an optical
controller system according to the present invention;

FIG. 5A depicts the first stage of operation of the optical
controller as depicted in FIGS. 4A and 4B for use in
finger print identification;

FIG. 5B further depicts the operation of the optical
controller according to FIGS. 4A and 4B for use in fingerprint
identification;

FIG. 5C depicts the final stage of operating optical
controller of FIGS. 4A and 4B as used in FIGS. 5A–5B,

FIGS. 5D, 5E, and 5F depict the use of the optical
controller of FIGS. 4A and 4B in aircraft and spacecraft
tracking operations;

FIGS. 6A and 6B depict a flow chart for computing the
optimal use of the spatial light modulation method according
to the present invention; and

FIGS. 7A–7E depict different embodiments which may be
used in the optical correlator system of FIGS. 4A and 4B.

DETAILED DESCRIPTION OF THE INVENTION

Before discussing the particular details of the present
invention, a brief overview of optical processing
components and the related Jones calculus will be provided. Linear
polarizers are devices which transmit a component of an
incident electromagnetic electric field in the direction of its
"transmission axis", and which block the component of the
electromagnetic electrical field which is orthogonal to its
"transmission axis". This preferential passing of components of
an electric field can be achieved by selective
absorption, selective reflection from an isotropic medium, or
selective reflection/refraction at the boundary of an anisotropic medium. "Wave retarders" are characterized by a
retardation amount, and the orientation of a "fast axis" and a
"slow axis". Upon transmission through a retarder,
a relative phase shift between the orthogonal components of
the electric field in the light beam occurs. "Polarization
rotators" are utilized to rotate the plane of rotation of linearly
polarized light by a fixed angle, while maintaining its
linearly polarized nature. Optical "analyzers" are utilized to
selectively transmit light which is polarized in only one
orientation, thus acting as a valve or filter. A "spatial light
modulator" is a device that modulates light at different
positions by predefined factors. Typically, it is a planar
optical element of controllable intensity transmittance and/or
relative phase shift. The emergent light at each location
can be characterized by the product of the Jones matrix
describing the optical properties of the spatial light modulator
times the Jones vector describing the polarization state
of the light input to the modulator. When a pixelated liquid
crystal video display is utilized as a spatial light modulator,
each pixel of the liquid crystal video display may be
described in terms of an optical transform, typically in terms
of the Jones matrix for the pixel. Commercially available
liquid crystal video displays typically utilize twisted
nematic liquid crystal cells placed between two parallel
glass plates and rubbed so that the molecular orientation
rotates about a helix normal to the plates, which is defined
as the "axis of twist". When an electric field (which is
created by one or more drive voltages applied to the pixel)
is applied in the direction of the axis of twist, the molecules
tilt toward the field. When the molecules are tilted at ninety
degrees, the polarizing effect of the liquid crystal cells is
eliminated. If the electric field is removed, the orientation of the
crystal layers near the glass dominate, thereby causing the
molecules to return to their original upright state, causing
the polarization effect to be regained. FIG. 1A graphically
depicts changing direction of the extraordinary birefringent
axis 16 of light through the thickness of a liquid crystal
video display 18.

An optical processing component may be characterized
mathematically in the terms of a Jones matrix. Jones matrices
describe the effects of mathematically linear optical
polarizing elements. Table 1 which is appended hereto
provides Jones matrices for a variety of rather simple and
conventional optical devices, including linear polarizers,
In optical information processing, it is important to have spatially localized control of the light. For example, preferably, in the present invention, the compound polarizer and compound analyzer are uniform over their active areas, which stands in contrast with the preferred spatial light modulator which is preferably a pixeled spatial light modulator with independent action at each pixel. However, in alternative embodiments, non-pixeled spatial light modulators may be utilized.

In the preferred embodiment of the present invention, the combined controller-implemented selection of Jones matrices optical transforms for the pixels of the spatial light modulator, the polarization effect of the compound polarizer, and the selection effect of the compound analyzer are utilized to obtain a particular one of a plurality of available transform operating curves, in order to obtain some optical processing objective.

In the preferred embodiment of the present invention, the improved spatial light modulator comprises in sequence a compound polarizer, the spatial light modulator itself, and a compound analyzer. It uses the pixelation of the Jones matrix spatial light modulator to provide spatial variation in the optical processing. The combination of the compound polarizer and the compound analyzer may be used to obtain a desired member of a family of operating curves in order to achieve a particular data processing objective.

Ordinarily a spatial light modulator may modulate light by varying its Jones matrix $J_p$ at each pixel. Ordinarily, the Jones matrix will be controlled by a single control parameter, such as voltage across the liquid crystal cell, so the set of input polarization states $S_4$ in Cartesian product with the resultant output polarization states $S_5$ is accordingly limited. The purpose of the present invention is to allow a wide latitude in selecting from the family of possible input/output combinations, and also to make such selection easily, efficiently, and rapidly accomplished.

Again, with reference to FIG. 1B, the polarization state $S_4$ is determined by the first compound element. Not just any input state $S_4$ will pass through the first compound element without losing energy to the compound element. The matrix $J_3$ describes the selection of part of the state $S_4$ that passes through the compound polarizer and appears as $S_5$. Similarly, the component state of $S_4$ that will pass the second compound element without being blocked, thus appearing as $S_6$, is determined by the compound analyzer, which is described by matrix $J_2$. The action of $J_2$ of the Jones matrix $J_1$ of the spatial light modulator is to connect the polarizer elements $S_5$ and $S_6$, with further aspects of the $S_5$ to $S_6$ modulation being determined by $J_1$ and $J_2$. Thus, if we can easily change $J_1$ and $J_2$, we can easily change the overall effective Jones matrix $J_1$. Typically, with analog spatial light modulators of the Jones-matrix type, there is a family of curves available. More particularly, the Jones matrix at each pixel is a function of one or more drive voltages applied to that pixel.

If we consider the case where $S_5$ and $S_6$ are similar polarization states, as determined by the values of the component elements of the compound polarizer and the compound analyzer, then the action of $J_2$ may clearly be seen to be expressed as a complex scalar, so its behavior is immediately plotted in the complex plane. If $S_5$ and $S_6$ are different polarization states, even though $J_2$ is a complex matrix, its voltage-controlled action will change the phase and amplitude of the light in the analyzed state $S_6$, and thus the combination of compound analyzer, spatial light modulator and compound polarizer may be regarded as affecting both the amplitude and phase of $S_6$, so again the assembly may be regarded as a complex spatial light modulator.

In optical information processing, it is important to have spatially localized control of the light. For example, in
optical correlator pattern recognition operations, a spatial light modulator is used to encode the signal pattern into the light beam at the input location, and similarly a spatially varying effect is implemented at the filter location. Spatially distributed control of the pixelated modulator is one key to having a spatial light modulator. Since \( J_b \) may have differing values at different locations on the modulator, so also may \( J \) vary across its face. A significant point of the present invention is that the compound spatial light modulator may be used in any location where light is to be modulated as a function of spatial position. In a serial correlator architecture, sometimes known (slightly erroneously) as a VanderLugt architecture, one might place a compound spatial light modulator in accordance with the present invention in both the input plane and the filter plane, or in either one.

As was stated above, the mode of operation of a twisted-nematic liquid crystal video display produces many interesting characteristics, which modulate both intensity and phase. Graphically, the optical effect of a particular pixel in a liquid crystal video display can be represented as a curve traced out in the complex plane. This is so because the modulation is complex, modulating both amplitude and phase together, but is restrained to a single path in the complex plane. We may call this path the “operating curve” of the device. These operating curves are determined by measuring the amplitude and phase modulation as a function of a particular drive parameter: the parameter that is varied to change the voltage across each pixel. In the preferred liquid crystal video displays utilized in the present invention, this voltage is representative of a gray scale value for the pixel which extend from a gray scale value of 0 to a gray scale value of 255. The plot produced is of the function:

\[
(T)^{1/2} \sin(\delta) + (S/T)^{1/2} \cos(\delta);
\]

where \( T \) represents the intensity transmission, and \( \delta \) represents the phase-shift produced at each gray scale level.

An example of such a plot is shown in FIG. 2A. To produce the appropriate amount of complex modulation, the relevant gray scale level is configured in a digitizer board and the liquid crystal video display produces one of the points on the curve, which we may consider to be points which are “realizable”. It is important to note that only points on the operating curve can be represented exactly in this operating mode of the liquid crystal video display. Any of the complex values of modulation can be approximated using only those values which are “realizable”.

FIG. 3 is a representation of the preferred embodiment of the present invention, with laser beam 25 providing a coherent light which is passed first through polarizer unit 27, the liquid crystal television 29, and finally through analyzer unit 31. A video signal 35 is provided to a drive circuit 33 for amplitude and/or phase modulation. This image information is then passed through polarizer unit 27, which is manufactured by Meadowlark Optics of Longmont, Colo. Also in the preferred embodiment of the present invention, a liquid crystal variable retarder is utilized, such as the model number LVRO.7.653 liquid crystal variable retarder manufactured and sold by Meadowlark Optics of Longmont, Colo., which provides a predefined amount of differential retardance in response to a control voltage.

With reference now to FIGS. 4A and 4B, Helium-Neon laser 45 is used as a source of coherent light. The laser beam diameter is expanded using two lenses in a system which defines beam expander 47. This produces a beam which is large enough to illuminate input modulator 41. The beam expansion also ensures that the intensity and phase do not vary greatly across the central portion of the beam that is used. The expanded laser beam then passes through input modulator 41, and “picks-up” the information displayed on liquid crystal television 49 of input modulator 41, owing to the amplitude and/or phase modulation. This image information on the laser beam is subject to the process of diffraction, and is accordingly decomposed into its spatial frequency components. The complete decomposition of the image into the spatial frequency components occurs at the far-field diffraction pattern (infinity); however, Fourier transform lens 51 is used to bring this far-field pattern into a more reasonable distance, such as the back focal plane of the lens which is defined as the plane which is located a distance of one focal length behind the lens. The input data are placed at the front focal plane (one focal length) away from Fourier transform lens 51. The result is that an optical Fourier transform is formed at the plane of filter modulator 43. The Fourier transform is important to the operation of a correlation system because of its well known properties in signal processing. Among these properties is its “shift-invariance”
which allows the system to be used for shift-invariant pattern recognition or object tracking.

The image that is displayed on the filter modulator 43 is a previously calculated version of the complex-conjugate of the Fourier transform of the object being tracked. If the input scene, which is derived from live video, is identical to the object of interest then the phase-structure of a laser beam will be to a greater or lesser degree "canceled-out" at the filter modulator 43, and a flat wavefront will emerge. This beam is again Fourier transformed by Fourier transform lens 53 to produce a bright spot, which is identified as the "correlation peak", at the correlation plane. This bright spot of light is formed at the center of the object of interest, and will move if the object moves. In other words, the bright spot of light formed one focal length from Fourier transform lens 53 will provide a tracking indicator. Typically, a charged coupled device, such as CCD camera 55 is located at the correlation plane to record the position of the bright spot to allow replay and storage of the tracking operations.

As is shown in one embodiment in FIGS. 4A and 4B, the input image is captured by input camera 57 which provides an analog signal to personal computer 61 which includes microprocessor 65. Microprocessor 65 controls the operation of video digitizer 59 which digitizes the analog input from input camera 57, and provides it through drive circuit 63 to the spatial light modulator (preferably a liquid crystal video display) of input modulator 41.

As was stated above, the filter modulator 43 is utilized to apply the complex-conjugate of the Fourier transform of the object being tracked to the light beam. This is accomplished by utilizing microprocessor 65, video digitizer 69 and drive circuit 73 to provide for spatial light modulation by liquid crystal spatial light modulator 77. Additionally, an electrically-actuable polarization rotation device 75 is provided and controlled by the microprocessor through digital input/output card 67 and digital interface 71, which is preferably an interface which is provided with the polarization rotation device). Electrical control signals are provided by personal computer 61 through digital interface 71 to polarization rotation device 75 to polarization rotation device 75 to influence the cumulative optical transform of filter modulator 43 in a manner which optimizes a provided optical processing objective which is provided to or derived by personal computer 61, as will be discussed further herebelow.

In the embodiment of FIGS. 4A and 4B, input modulator is shown as including analyzer 79 and analyser 83 which substantially uniformly polarize and filter the light beam. Additionally, filter modulator 43 is depicted as including analyzer 79.

The operation of the optical correlator of FIGS. 4A and 4B will now be described with reference to FIGS. 5A, 5B, and 5C in the context of fingerprint identification. First, a digital version of the object of interest (the fingerprint) is acquired using the combination of video camera 57 and video digitizer board 59 which is resident in personal computer 61. This digital image is then read into a computer program which will be used to create the filter. The classical matched-filter is usually used as the starting point for filter generation. This filter is the complex conjugate of the Fourier transform of the object of interest. However, as mentioned previously, current available spatial light modulators cannot attain arbitrary complex values of modulation. Instead, they are constrained to the set of "realizable values" specified by the drive parameter, as is shown in FIGS. 2A through 2C. Thus, the best that can be done is to approximate the ideal filter by making the best use of what is "realizable" with filter modulator 43 of FIGS. 4A and 4B.

There are many procedures used to implement this approximation, but the methods described in the following references are favored, which are incorporated herein by reference as if fully set forth:


Reference 3: "MEDOF: Minimum Euclidean Distance Optical Filter", Computer code available under NT control number MSC-22380 from Cosmic (Computer Software Management Information Center), University of Georgia, 382 East Broad Street, Athens, Ga. 30602-4272.

This algorithm is utilized in Reference 3 which is the computer program called MEDOF which is available through COSMIC. This algorithm produces a filter which accounts for the actual modulation characteristics of the modulators used in the correlator. This is in contrast with previous techniques which assume ideal behavior of the modulator. The filter control produced by these techniques is sent to the filter modulator 43 of FIGS. 4A and 4B, and will produce a correlation spot if the object of interest is present in the live scene under examination. Therefore, as is depicted graphically in FIG. 5B, the digitally acquired image 101 is subjected to a filter generation software 103 to generate the set of filter drive signals 105 which, when applied to filter modulator 77 through drive circuitry 73, cause the correlator to recognize the reference object. The set of filter drive signals 105 will optimally depend on several factors, explicitly including the set of filter values 107 from which to choose and the pattern recognition metric being optimized.

In the present invention, the operating curve of filter modulator 43 of FIGS. 4A and 4B is not restricted to one specific configuration, such as encountered in the prior art when a pre-set operating curve is provided for the filter modulator. Instead, the range of available operating curves is expanded, by providing a means for changing the operating curves, which is under the control of personal computer 61 (of FIGS. 4A and 4B). This is accomplished in a preferred embodiment by substituting an electrically- addressable polarization modifying device in lieu of a conventional polarizer, as a component of filter modulator 43 (of FIGS. 4A and 4B). This is equivalent to changing the polarization state with a prior art device which can be adjusted simply by changing the voltage applied across polarization rotation device 75, rather than by mechanical manipulation of the polarization rotation device. As stated above, such devices are commercially available. One example is a Meadowlark Optics liquid crystal Sénarmont polarization rotator. Such a device can be controlled by a computer which supplies a digital word via a digital input/output card to a digital interface unit for the polarization rotator. In FIG. 5B we indicate that a specific digital word has resulted in the selection of operating curve 107. In the digital interface 71, the digital word is then converted to an analog voltage suitable for driving the polarization rotator 75 (of FIG. 5C), which will produce a certain rotation of the light polarization. This will change the linear polarization state which is incident on liquid crystal video display 77 in filter modulator 43. As is seen in FIGS. 2A through 2C, this dramatically affects the operating curve of filter modulator 43. Therefore, each of the operating curves shown in FIGS.
Thus, the curve shown in FIG. 2A would perform well in effect of polarization rotation device 75. The reason for wanting to reconfigure the filter modulator 43 (of FIGS. 4A and 4B) to operate with different operating curves is that each curve can trace out only a restricted path in the complex plane. The filter is calculated so that the best approximation to the ideal filter is obtained. This involves comparing the ideal filter values (which desire arbitrary complex transmittances of the filter modulator 43) with the realizable values (which constitute the values traced out by the operating curve). Thus, for each operating curve a different solution may be obtained. Furthermore, it is anticipated that certain operating curves will produce a better approximation to the ideal filter than others. The hypothetical example of this effect is illustrated graphically in FIG. 2D. The black points in this complex plot represent the realizable values (which are "achievable" or "realizable") using the first three operating curves shown in FIGS. 2A through 2C, FIG. 2A would give a much better approximation to the ideal filter values than the other two operating curves. While this example is exaggerated to demonstrate the concept, there will be instances where an operating curve such as that shown in FIG. 2A would give a far superior performance in a correlator than the other two operating curves of FIGS. 2B and 2C. Specifically, this could be when some optical system noise is present in the live input scene. If this noise is spectrally characterized, then the regions in the filter at which this noise appears will be well defined. If the operating curve has on it some regions which produce very low transmittance (such as seen in FIG. 2A but not in FIGS. 2B and 2C), then the noise can be filtered out of the system. Thus, the curve shown in FIG. 2A would perform well in situations where input noise was to be suppressed, while still providing a useful correlation. The signal-to-noise ratio is a metric that is fairly well established in the optical processing community. Other metrics include the height of the correlation peak produced by the correlator. It is intended that the user of the filter generation algorithm would select a particular metric that he is interested in, and an example of the object of interest. The filter generation algorithm would then select the best operating curve from the set available, for that particular task (an optical processing objective), and would produce a filter suitable for implementation on it. A flow-chart is shown in FIGS. 6A and 6B which describes the intended procedure. The data supplied to the correlator device would be the filter and the digital word.

Turning now to Figs. 6A and 6B, the process begins at step 201 wherein the input image of the object scene, or pattern of interest is digitized. Then, in accordance with step 203 a discrete Fourier transform is calculated for the input image of the object of interest. Then, the complex values which are desired are represented as best possible with those values which are "achievable" or "realizable" using the first of a plurality of operating curves. Next, in accordance with step 207, the filter values are stored along with the digital word which produces the operating curve. Then in accordance with step 209 the metric of interest is calculated, such as the correlation peak height, or the signal-to-noise ratio. Next, in accordance with step 211 all of the available operating curves have been examined; if they have all been examined, the process continues at step 221 by exiting from this routine; however, if it is determined in step 219 that not all of operating curves have been examined, the process returns to step 211 where another operating curve is examined. If in step 213 it is determined that the value of the metric of interest is greater than the previous value, the process continues at step 217 wherein the filter values and associated digital word are stored in memory. In this manner, each of the available operating curves (from a finite set of operating curves such as six to ten curves) is successively examined to determine its suitability in terms of the metric selected by the operator. The operating curve which achieves the metric goal established by the operator is recorded in memory along with the digital word which is used to realize this operating curve.

Reference 1 describes a theory of how to use a given operating curve, and References 2 and 3 relate to a practical code that implements the theory of Reference 1. However, none of these References tell how to evaluate the utility of that curve and thus select the best curve for a particular application. The following material supplements these References.

Reference 1 describes that, given an operating curve, we search over a pair of numbers $G$ and $\zeta$ performing the computations given below. (In Reference No. 1, see also the Cookbook Summary in Appendix C). We have selected a metric $T$, for example one of those given in Eqs. 7 through 11 of Reference 1. For each frequency $m$ in the set of all frequencies at the filter plane, one then:

1. Computes $H^m$ as in Eq. 15 (It is a function of $G$ and $\beta$); and
2. Determines the value $H^m$ on the curve that is closest by Euclidean measure in the complex plane to $H^m$. The Cookbook summary of Appendix C of Reference 1 is repeated below since it provides a detailed and practical summary of the technique disclosed in Reference 1:
Box 209 represents an evaluation of $T(G,13)$ for the present 35
represents the search over $G$ and $13$ and items 1 and 2 above. (7)
understand the realizable values of the modulator $H=M \exp(j\phi)$ in appropriate physical terms. See Appendix B.

(8) Achieve an algorithm that finds the Euclidean-closest
realizable filter value, given an arbitrary location in the
complex plane.

(9) From the histograms of signal's amplitude $A$ and the
filter's magnitude $M$, determine a search range of gain,
$G_{\text{max}}$ to $G_{\text{min}}$. For example, if $\text{SNR}$ is the metric, Eq.
(15) indicates $G_{\text{max}} \left[ A/P \right]_{\text{max}} = M_{\text{max}}$ and vice versa.

(6) The search range for output phase $\beta$ is $[0, 2\pi]$ unless
it can be restricted by other knowledge.

(7) Execute a two-dimensional search over $G$ and $\beta$.
(a) For each frequency $m$, calculate $H^*$ from Eq. (15)
and set $H_{\text{max}}$ equal to the closest realizable filter value.
(b) From the set $H_{\text{max}}(G,\beta)$, calculate $T(G,\beta)$.

(8) Determine $G^*$ and $\beta^*$ that maximize $T$.
(9) Select $H_{\text{max}}(G^*, \beta^*)$ as the filter.

In that manner one computes the optimal filter for the
given pair $(G,\beta)$, and one may evaluate the metric $T(G,\beta)$ for
that filter. The search over $G$ and $\beta$ is a finite search, and we
select $G^*$ and $\beta^*$ that produce the largest value of $T$. This is
described in flowchart form in FIGS. 6A and 6B. Box 208
represents the search over $G$ and $\beta$ and items 1 and 2 above.
Box 209 represents an evaluation of $T(G,\beta)$ for the present
operating curve. The loop represents the trial of all the
operating curves, and the selection of the best of all of them.

One can generalize that procedure to include optimizing a
filter over the other parameters that determine its operating
curves. In the present case, one would ordinarily choose a
parameter that is easily modified, the two simplest such being $V_p$ and $V_p$. In accordance with the present invention, we select operating curves by motorized control of $\Psi_p$ and $\Psi_p$, but the voltage control of polarization rotation devices either singly as in FIGS. 4A and 4B and 5C, or in the more
complicated architectures of FIG. 7, could supplant the
motor drive. Changing the other parameters from filter to
does not consume a lot of data storage; typically there are
between 128=16,384 and 5122=262,144 filter values to store, and we are talking about adding another 1 to 4 stored
values to select the operating curve.

So far only discrete operating curves have been considered:
that is, those at specific orientations for the polarizer and
analyzer. However, it can be shown that all of the
available operating curves can be expressed in an analytic
form by using the Jones calculus. This produces a two-by-
two matrix which describes the polarizing nature of an
optical element, in this case a liquid crystal video display.
The Jones matrix can be evaluated by a series of empirical
observations and measurements, or by determining the values of some physical
calculations which construct a physical model, as is set forth
in the following articles which are incorporated herein by
reference as if fully set forth:

Reference 4: R. Clark Jones, "A New Calculus for the
Treatment of Optical Systems VI. Experimental Determina-
37, pages 110–112 (1947);

Reference 5: Khangua Lu and Bahaa E. A. Saleh, "T
Theory and Design of The Liquid Crystal TV and An Optical
Spatial Phase Modulator", Opt. Eng., vol. 29, pages

Once the Jones matrix has been determined for the filter
modulator, further sets of operating curves for the liquid
crystal video display can be investigated by the filter gen-
eration algorithm, thus extending the possibilities of modu-
larization.

FIGS. 5D, 5E, and 5F depict the utilization of the present
invention in the tracking of aircraft of spacecraft. As is
shown in FIG. 5F, video camera 57 is utilized to acquire an
image of the craft. Then, in accordance with FIG. 5E the
digitally acquired image 101 is subjected to a filter generation
software 103 to generate a set of filter drive signals 105
when, which implied to filter modulator 77 through drive
circuitry 73, cause the correlator to "recognize" the craft.
Next, as is depicted in FIG. 5F, the input image 108 of the
craft is captured by video camera 57 and routed to video
digitizer 61 which provides through drive circuit 63 of video
image which is impressed upon a light beam. Additionally,
a video digitizer 67 of personal computer 61 provides a
signal to drive circuit 73 which is provided to a spatial light
modulator (preferably a liquid crystal display 77) of filter
modulator 43. Additionally, digital input/output card 67 of
personal computer 61 provides a digital word to digital
interface 71 which converts the digital word into an analog
signal which alters the polarization affect of polarization
rotation device 75.

The different sets of operating curves can be selected in an
optical correlator system by using further embodiments of
the invention. The first embodiment of the invention which
has been discussed so far is depicted in FIG. 7A, and
includes polarization rotation device 301, liquid crystal
television 303, and analyzer 305. In a second embodiment of
the invention, which is depicted in FIG. 7B, the spatial light
modulator consists of an electrically-actuable polarization
rotation device 307, a liquid crystal television 309, and an
electrically-actuable polarization rotation device 311. This
device provides significant commercial advantage in that
both the polarizer and analyzer are replaced with electrically-actuable polarization rotation devices. This con-
figuration can access all of the operating curves which are
possible with different orientations of linear polarization
at the input and output of liquid crystal television 309. Note
that polarization rotation device 311 is placed in the optical
system facing the direction opposite from that of polarization
rotation device 307; this is because the polarization rotation
device has a linearly polarizing element on the input
face of the polarization rotation device 307 itself. When such
a rotator is substituted for an analyzer, this linearly polar-
zation element is required to be on the exit face of the device.
The third embodiment of FIG. 7C includes an electrically-actuable polarization rotation device 313, electrically-
actuable variable retarder 315, liquid crystal television 317,
and analyzer 319. Preferably, a variable retarder such as
those available from Meadowlark Optics is utilized and will
utilize the same addressing mechanism as polarization rotation
device 313. Thus, a digital word supplied to the inter-
face unit of variable retarder 315 causes a specified differ-
ential wavefront retardation. The combination of the rotator
313 and the retarder 315 is capable of producing any
arbitrary (elliptical, circular, or linear) polarization state of
light. Thus, this configuration can produce operating curves
which are a result of arbitrary input states of polarization.
Note that the set of operating curves produced by this
configuration would be different from those obtained with a
system shown in FIGS. 7A and 7B.

Still another embodiment of the present invention is
depicted in FIG. 7D, which includes an electrically-actuable
polarization rotation device 321, an electrically-actuable
variable retarder 323, a liquid crystal video display 325, and
a polarization rotation device 327.

A final embodiment of the present invention is depicted in
FIG. 7E, and includes electrically-actuable polarization rotation
device 329, electrically-actuable variable retarder 331, liquid
crystal video display 333, electrically-actuable variable
retarder 335, and electrically-actuable polarization rotation
device 337. This configuration could be used as an
electrically controlled polarimeter, which is a device that
produces a full polarization characterization of an optical
specimen, but which is not necessarily a liquid crystal video
display. Such a polarimeter could be used for the calibration
of optical components, or could be used to calculate the
Jones matrix of an optical device. An electrically-controlled
polarimeter would be much faster and potentially much
cheaper than those prior art devices currently in use. This
configuration could be used to maximize the light through-
put of a filter modulator system, by permitting arbitrary
states of polarization input to the liquid crystal video display
and allowing the analysis for arbitrary polarization states
leaving the liquid crystal video display 333. Although the
configuration shown in FIG. 7E provides the full capability
to control the input polarization and analyze the output
polarization, it is also the most complicated of all these
systems presented, as it requires four elements of polariza-
tion control. In practice, it will often be more advantageous
to accept less flexibility in the control of the input and output
polarization states and thus decrease the number of control
parameters required. A wide selection of potential operating
curves will still be possible using the simpler configurations
presented to FIGS. 7A through 7D, and others that are not
pictured here for example: (rotator, modulator, retarder,
retarder); (rotator, modulator, retarder); or (polarizer,
modulator, retarder, rotator).

A further advantage of the present invention is that of
"tuning" a filter modulator's operating curve to one which
previously specified. This is accomplished by adjusting the
digital word sent to the two digital interface boards for the
polarization rotators (in the case of the configuration shown
in FIG. 7D), and then adjusting them until a "standard"
performance of the correlator is achieved. In other words,
a particular filter control is calculated for the correlator that
gives a very specific response in the correlation output (for
example, a dark spot at the center of the correlation plane).
This filter control is written for the standard operating curve
of the filter modulator, so that any deviation from this
operating curve would produce a well characterized change
in the output, such as a non-zero intensity at the center of the
correlation plane. The polarization rotators are then be
adjusted to reproduce the original response. This procedure
helps to ensure reliable uniformity in the day-to-day opera-
tion of a correlator apparatus.

While the invention has been shown in only one of its
forms, it is not thus limited but is susceptible to various
changes and modifications without departing from the spirit
thereof.

What is claimed is:
1. A method in an optical correlation system of correlating
an input image with an optical filter, comprising:
providing a filter modulator which includes (a) a spatial
light modulator, and (b) an electrically-actuated polar-
ization apparatus;
defining a preselected number of optical transforms avail-
able from said filter modulator for a plurality of dif-
fering polarization states of said electrically-actuated polar-
ization apparatus;
impressing said input image upon a light beam utilizing
an input modulator;
deckomposing said input image into its frequency compo-
nents;
providing a processor for operation of said filter modu-
lator;
providing an optical processing objective to said proces-
sor;
utilizing said processor to successively examine said
preselected number of optical transforms and select a
particular one of said preselected number of optical
transforms which best satisfies said optical processing
objective;
utilizing said processor to provide commands to said electrically-actuated polarization apparatus in order to cause said filter modulator to provide said particular one of said preselected number of optical transforms; filtering said light beam with said filter modulator; and detecting and monitoring a correlation indicator.

2. A method in an optical correlation system of correlating an input image with an optical filter, according to claim 1: wherein, during said step of utilizing said processor to successively examine, said processor is utilized to successively analyze each of said preselected number of optical transforms with respect to a particular provided metric, in order to determine which particular one of said preselected number of optical transforms best satisfies said optical processing objective.

3. A method in an optical correlation system of correlating an input image with an optical filter, according to claim 1: wherein said electrically-actuated polarization apparatus of said filter modulator functions as a polarizer which polarizes said light beam into a desired polarization state prior to communication of said light beam to said spatial light modulator.

4. A method in an optical correlation system of correlating an input image with an optical filter, according to claim 1: wherein said electrically-actuated polarization apparatus of said filter modulator functions as an analyzer which selects a polarization state from said light beam subsequent to communication of said light beam to said spatial light modulator.

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