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.

4 Claims, 14 Drawing Sheets
FIG. 1B

S1 → 15 → 17 → S2 → S3 → S4 → JC → JB → JB → Jc
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.

Was this the last available 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

1. Field 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.

2. Description of the Prior Art

Many optical processing systems 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, its 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. The controller member also supplies at least one drive parameter value to the spatial light modulator. A light beam is passed through the spatial light modulator and 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 is utilized 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 correlator system according to the present invention;

**FIG. 5A** depicts the first stage of operation of the optical correlator as depicted in FIGS. 4A and 4B for use in fingerprint identification;

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

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

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

**FIGS. 6A and 6B** depict a flowchart 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,
quarter-wave retarders, half-wave retarders, isotropic retarders, relative phase changers, and circular polarizers. In the table, where applicable, a plurality of different "orientations" are defined for each type of optical device. The table also includes a Jones matrix which defines the effect of the optical device at the particular defined orientation. When light is propagated through mathematically linear optical polarizing elements, the light wave's polarization state is sequentially multiplied by the optical elements' Jones matrices. This can best be described with reference to FIG. 1B. The polarization state of light beam 15 is defined by polarization states $S_1$, $S_2$, $S_3$, and $S_4$, wherein $S_1$ represents the polarization state of light which is incident to optical processing device 17 which has a Jones matrix of $J_p$. The light which emerges from optical processing device 17 has a polarization state of $S_2$, which is the vector product of the polarization state $S_1$ and the Jones matrix $J_p$. The polarization state of the light incident to optical processing device 19 is $S_3$. The optical effect of optical processing device 19 is represented by Jones matrix $J_p$. The light emerging from optical processing device 19 has a polarization state of $S_4$, which is the vector product of the polarization state $S_3$ and the Jones matrix $J_p$. The polarization state of light incident to optical processing device 21 is $S_5$. The component elements of the compound polarizer and the polarizer comprises a retarder, a polarization rotator, and a linear polarizer. 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 utilized to obtain a desired member of a family of operating curves in order to achieve a particular data processing objective.

In the preferred embodiment of the present invention, the combination of optical devices 17, 19, 21 is represented by Jones matrices $J_p$. The polarization state of light emerging from optical processing device 21 is $S_3$, which is the vector product of the polarization state of the incident light $S_2$ and the Jones matrix $J_p$. Since these optical processing devices 17, 19, 21 are mathematically linear, the composite optical effect of optical devices 17, 19, 21 is the matrix product of Jones matrices $J_p$, $J_p$, and $J_p$. The polarization state of light beam 15 is defined by polarization states $S_1$, $S_2$, $S_3$, and $S_4$, wherein $S_1$ represents the polarization state of light which is incident to optical processing device 17 which has a Jones matrix of $J_p$. The light which emerges from optical processing device 17 has a polarization state of $S_2$, which is the vector product of the polarization state $S_1$ and the Jones matrix $J_p$. The polarization state of the light incident to optical processing device 19 is $S_3$. The optical effect of optical processing device 19 is represented by Jones matrix $J_p$. The light emerging from optical processing device 19 has a polarization state of $S_4$, which is the vector product of the polarization state $S_3$ and the Jones matrix $J_p$. The light which emerges from optical processing device 19 has a polarization state of $S_5$, which is the vector product of the polarization state $S_4$ and the Jones matrix $J_p$. The polarization state of light incident to optical processing device 21 is $S_5$. The matrix associated with optical processing device 21 is represented by Jones matrix $J_p$. The polarization state of the light emerging from optical processing device 21 is $S_6$, which is the vector product of the polarization state of the incident light $S_5$ and the Jones matrix $J_p$. 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.

If we consider the case where $S_1$ and $S_4$ 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 $J_p$ may clearly be seen to be expressed as a complex scalar, so its behavior is immediately plotted in the complex plane. If $S_1$ and $S_4$ are different polarization states, even though $J_p$ is a complex matrix, its voltage-controlled action will change the phase and amplitude of the light in the analyzed state $S_4$, and thus the combination of compound analyzer, spatial light modulator and compound polarizer may be regarded as affecting both the amplitude and phase of $S_4$ 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 spatial 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 $J_1$ 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 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:

$$(T)^{1/2} \sin(S/(T)^{1/2}) \cos(B);$$

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 modified to a certain degree by the voltage used to bring this far-field pattern into a more reasonable realization is then modified to a certain degree by the voltage applied to the filter modulator 33. 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 this 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. This 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 of 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 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 polarizer 81 and analyzer 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 may 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 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. 4.0055.086
Thus, the curve shown in FIG. 2A would perform well in
43 (of FIGS. 4A and 4B) to operate with different operating
effect of polarization rotation device 75.

device would be the filter and the digital word.

intended procedure. The data supplied to the correlator
chart is shown in FIGS. 6A and 613 which describes the
produce a filter suitable for implementation on it. A flow-
select the best operating curve from the set available, for that
object of interest. The filter generation algorithm would then


So, in broad overview and with reference to FIG. 5C,
input image 108 is captured by video camera 57 and routed
to video digitizer 61 which provides through drive circuit 63
a video image which is impressed upon a light beam.
Additionally, video digitizer 69 of personal computer 61
provides a signal to drive circuit 73 which is provided to a
spatial light modulator (preferably a liquid crystal video
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
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 represented graphically in FIG.
2D. The black points in this complex plot represent ideal
complex filter values. Its seen that of the 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 correla-
tion 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 accor-
dance 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 the complex values which
are desired are represented as best possible with the
“achievable” or “realizable” values which are in the next
operating curve. Then in accordance with step 213, the
metric of interest is calculated, such as the correlation peak
height, or the signal-to-noise ratio, or any other suitable
metric. In step 215, the software determines whether the
value of the metric for the present operating curve is greater
than the previous value; if not, the process continues at
software block 219; if so, the process continues at software
block 217. In step 219, it is determined whether all of the
available operating curves have been examined; if they have all been examined, the process continues at step 221 by
executing 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
present metric is greater than the previous value, the process
continues at step 217, wherein the filter values and associ-
dated 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 best
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.

In order to understand References 1, 2, and 3 and their
relationship to the flowchart of FIGS. 6A and 6B of the
present invention, suppose one has the following fixed set:
bias voltage V_b, drive voltage for the polarization rotation
cell V_p, and angles of polarization \( \Psi_p \) and analyzer \( \Psi_a \). Then
the set of complex values traced as a pixel’s video drive
current varies through its range and is known as the 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,
one of these References tells how to evaluate the utility of
that curve and thus select the best curve for a particular
application. The following material supplements these Refer-
ences.
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 section
3 in the vicinity of Eq. 15, and also Section 4. 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 \( (it \ is a function of G and \beta) \);
2. Determines the value \( H^m \) on the curve that is closest by
Euclidean measure in the complex plane to \( H^m \).
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.
describe in flowchart form in FIGS. 6A and 6B. Box 205
in the following articles which are incorporated herein by

The Jones matrix can be evaluated by a series of empirical
form by using the Jones calculus. This produces a two-by-

available operating curves can be expressed in an analytic 55
and analyzer. However, it can be shown that all of the
quired: that is, those at specific orientations for the polarizer

values to select the operating curve.

store, and we are talking about adding another $L$ to 4 stored 50
are between $2^{16} = 65,536$ and $2^{10} = 1,024$ filter values to

filter does not consume a lot of data storage; typically there

complicated architectures of FIG. 7, could supplant the

w, but the voltage control of polarization rotation devices

we select operating curves by motorized control of $U_L$, and

being $V_b$ and $V_p$. In accordance with the present invention,

operating curve. The loop represents the trial of all the

select $G*$ and $13$* that produce the largest value of $T$. This is

which, when implied to filter modulator 77 through drive
circuitry 73, cause the correlator to "recognize" the craft. 10
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 circuitry 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 polariza-
tion 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 307, liquid crystal
television 303, and analyzer 305. Particularly, 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

Reference 4: R. Clark Jones, "A New Calculus for the
Treatment of Optical Systems VI. Experimental Deter-
37, pages 110–112 (1947).
which are a result of arbitrary input states of polarization. Noted 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 throughput 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 331. 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 polarization 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, rotator); (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 operation 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.

<table>
<thead>
<tr>
<th>Optical Device</th>
<th>Orientation</th>
<th>Jones Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Polarizer</td>
<td>Horizontal Transmission</td>
<td>$\begin{bmatrix} 1 &amp; 0 \ 0 &amp; 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Linear Polarizer</td>
<td>Vertical Transmission</td>
<td>$\begin{bmatrix} 0 &amp; 0 \ 0 &amp; 1 \end{bmatrix}$</td>
</tr>
<tr>
<td>Linear Polarizer</td>
<td>Transmission at 45° angle</td>
<td>$\begin{bmatrix} 1 \pm j \ 1 \pm j \end{bmatrix}$</td>
</tr>
<tr>
<td>Quarter-Wave Retarder</td>
<td>Fast Axis at Vertical</td>
<td>$\begin{bmatrix} 1 \ 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Quarter-Wave Retarder</td>
<td>Fast Axis at Horizontal</td>
<td>$\begin{bmatrix} 1 \ 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Quarter-Wave Retarder</td>
<td>Fast Axis at 45° angle</td>
<td>$\begin{bmatrix} 1 \pm j \ \pm j \end{bmatrix}$</td>
</tr>
<tr>
<td>Half-Wave Retarder</td>
<td>Fast Axis at either Horizontal or Vertical</td>
<td>$\begin{bmatrix} 1 \ 0 \end{bmatrix}$</td>
</tr>
<tr>
<td>Isotropic Retarder</td>
<td></td>
<td>$\begin{bmatrix} e^{j\theta} &amp; 0 \ 0 &amp; e^{-j\theta} \end{bmatrix}$</td>
</tr>
<tr>
<td>Relative Phase Changer</td>
<td></td>
<td>$\begin{bmatrix} e^{j\phi} &amp; 0 \ 0 &amp; e^{-j\phi} \end{bmatrix}$</td>
</tr>
<tr>
<td>Circular Polarizer</td>
<td>Right</td>
<td>$\begin{bmatrix} 1 &amp; j \ 2 &amp; -j \end{bmatrix}$</td>
</tr>
<tr>
<td>Circular Polarizer</td>
<td>Left</td>
<td>$\begin{bmatrix} 1 &amp; -j \ 2 &amp; j \end{bmatrix}$</td>
</tr>
</tbody>
</table>

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 polarization apparatus;
   - defining a preselected number of optical transforms available from said filter modulator for a plurality of differing polarization states of said electrically-actuated polarization apparatus;
   - impressing said input image upon a light beam utilizing an input modulator;
   - decomposing said input image into its frequency components;
   - supplying said frequency components to an input plane of said filter modulator;
   - providing a processor for operation of said filter modulator;
   - providing an optical processing objective to said processor;
   - 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 pro-
vided 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 sub-
sequent to communication of said light beam to said
spatial light modulator.

* * * * *