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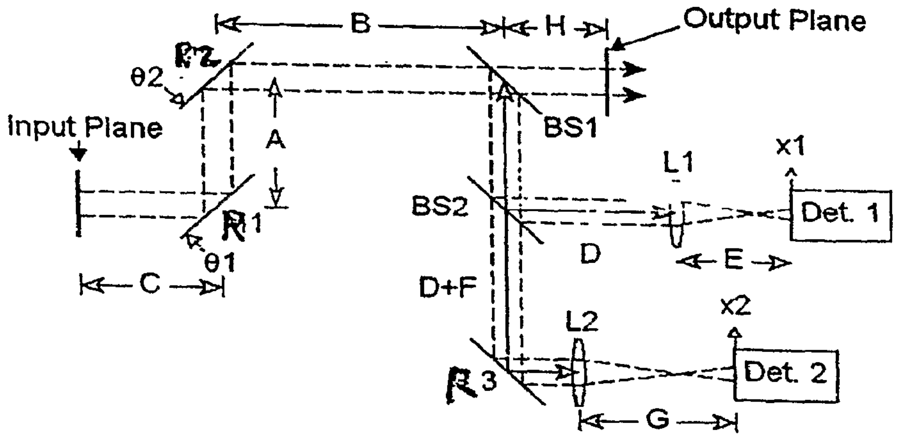
(54) Title: OPTICAL BEAM STEERING AND SAMPLING APPARATUS AND METHOD



(57) Abstract: In a light (optical) beam steering/sampling system, a matrix inversion control technique is used to decouple the operation of the actuators which drive the steering mirrors. The control technique uses two virtual variables, each having an associated independent feedback loop operating in a non-cross-coupled manner, each variable being associated with one of the two steering mirrors.

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OPTICAL BEAM STEERING AND SAMPLING APPARATUS AND METHOD

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. provisional application no. 60/760,521 filed January 20, 2006, incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] This disclosure relates in general to the field of optics and more particularly to a method and apparatus for control of an optical system.

BACKGROUND

[0003] It is well known in the optics field to control electro-magnetic beams, typically light beams. It is often necessary to sample a portion of a light beam for subsequent control purposes. This typically involves some sort of detector and a feedback loop. Beams are typically detected in terms of their displacement and angle. In the prior art, for instance, to control the beams the lenses present in such a system are sometimes used in conjunction with steering mirrors. Typically, for instance, there are two steering mirrors in the system and two detectors. In one known system it is arranged so that one detector only observes changes in the beam due to the tilt of the first steering mirror. But then it has been found that it is impossible to make the second detector output signal dependent only upon the tilt of the second steering mirror. In other words, this arrangement has undesirable in terms of feedback, making the feedback complicated and almost impossible to eliminate all cross coupling. For example, when a position or angle change occurs to the input light beam which is captured by a non-zero reading from the first detector with a reading of the second detector remaining unchanged, the first steering mirror will have to be moved to eliminate the non-zero reading. This leads to an angle change in the output beam which will be detected in the second detector leading to a correction signal applied to the second mirror. Even if the system is carefully tuned so as to be stable, changes in the relative locations of the steering mirrors and detectors require a complete re-tuning, and may even result in configurations for which no stable tuning is possible. In particular, the arrangement in which one detector only observes changes due to tilt of one steering mirror is only possible at one unique distance between steering mirror and detector, based on the focal length of an interposed lens. This is generally a complicated system and it has undesirably proven almost impossible to eliminate all its error, or to be re-configured in fielded applications which require variation in the optical layout.

SUMMARY

[0004] In accordance with this invention a matrix inversion control technique is used to decouple the operation of the actuators which drive the steering mirrors in a beam steering/sampling system. Decoupling of the steering mirror actuators allows further for a calibration technique to identify physical configurations and a reconfigurable method. The calibration further allows for a fixed sampling module which samples the position of the optical beam at locations arbitrarily positioned relative to the actuators. Thus, by using the matrix inversion to decouple the control, a system with the possibility of eliminating almost all error is provided both by factory adjustment, and later if needed, by calibration on site.

[0005] In accordance with the present invention two virtual variables are constructed for purposes of feedback control, each variable having an associated independent feedback loop operating in a non-cross-coupled manner. Hence, each of these variables is respectively identified with one and only one of the steering mirrors so that the changes in the state (e.g., tilt) of one steering mirror do not affect the other variable. Hence, each feedback loop can operate independently. The virtual variables do not in general, correspond to beam pointing and displacement, although they can be used to calculate the pointing and displacement.

[0006] This system is applicable, for instance, to semiconductor manufacturing lithography equipment which typically provides light in the form of ultraviolet to expose resist on a wafer. This is merely an exemplary application. The present system and method are applicable to manipulation of any type of collimated light including, for instance, laser (coherent) light but not so limited. The present method and apparatus are generally useful with optical systems having continuous or pulsed beams, ultraviolet to infrared wavelengths, large or small diameter light beams and varying system configurations. Exemplary applications include wavelength multiplexing and de-multiplexing, power splitting and monitoring, beam measurement and monitoring, laser cutting, machining or surgery, interferometry, and multi-port light management.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Fig. 1 shows in a block diagram an example of the present optical system.

[0008] Fig. 2 shows in a block diagram the feedback control method for the two feedback loops.

[0009] Fig. 3 shows the optical axis of the Fig. 1 system.

DETAILED DESCRIPTION

[0010] The present beam steering sampling system, for one of the two controlled planes, is shown in Figure 1. For instance, this depicts the system in the *x-z* plane. A control loop (not shown) including two additional actuators, one per steering mirror, and two additional detectors, is provided for similar control in the *y-z* plane. For simplicity, this description limits itself to one such plane, but extension to the other plane is routine and accomplished with the same method as described herein. All optical elements in Fig. 1 are conventional and suitably mounted on an optical bench or other support. In one embodiment the detectors Det1, Det2 are on a separate support from the other optical elements. In one embodiment Det1, Det2 are derived from the four quadrants of a conventional split quadrant photodetector. A position sensing photodectector or other type may also be used. The steering mirrors, each driven by a suitable precision actuator A1, A2 in the plane depicted in Fig. 1, are R1, R2. The input light beam (shown by parallel broken lines to depict its beam width) is at the input plane. There are provided beam splitters BS1, BS2. The main light beam (split off from the portion incident on the detectors) is supplied at the output plane. Mirror R3 is located to direct the light to detector Det2. Given the distances *A, B, C, D, E, F, G,* and *H* defined in Fig. 1 (where *D* is the distance between beam splitter BS1 and focusing lens L1 along the optic axis, and *D+ F* is likewise the distance between beam splitter BS1 and focusing lens L2), the focal lengths of lens L1 and lens L2 f_1 and f_2 respectively, the mirror-angle to translation coupling coefficient $T \equiv dz / d\theta$, and the angles of the steering mirrors R1 and R2, θ_1 and θ_2, the position and angle respectively of the beam relative to the optic axis, x_{out} and θ_{out}, as a function of the beam input position and beam angles, x_{in} and θ_{in}, is given by:

$$\begin{bmatrix} x_{out} \\ \theta_{out} \end{bmatrix} = \begin{bmatrix} 1 & A+B+C+H \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_{in} \\ \theta_{in} \end{bmatrix} + 2 \begin{bmatrix} A+B-T+H & B-T+H \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

[0011] Similarly, the beam position x_1, x_2 at each of the two detectors' active elements is given by:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \end{bmatrix} \begin{bmatrix} x_{in} \\ \theta_{in} \end{bmatrix} + \begin{bmatrix} \gamma_1 & \delta_1 \\ \gamma_2 & \delta_2 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix},$$

where:

$$\alpha_1 \equiv 1 - \frac{E}{f_1},$$

$$\beta_1 \equiv A + B + C + D + E\left(1 - \frac{A+B+C+D}{f_1}\right),$$

$$\gamma_1 \equiv 2\left[A + B - T + D + E\left(1 - \frac{A+B-T+D}{f_1}\right)\right],$$

$$\delta_1 \equiv 2\left[B - T + D + E\left(1 - \frac{B-T+D}{f_1}\right)\right],$$

and:

$$\alpha_2 \equiv 1 - \frac{G}{f_2},$$

$$\beta_2 \equiv A + B + C + D + F + G\left(1 - \frac{A+B+C+D+F}{f_2}\right),$$

$$\gamma_2 \equiv 2\left[A + B - T + D + F + G\left(1 - \frac{A+B-T+D+F}{f_2}\right)\right],$$

$$\delta_2 \equiv 2\left[B - T + D + F + G\left(1 - \frac{B-T+D+F}{f_2}\right)\right].$$

[0012] If one defines two new variables, u and v, such that:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{\gamma_1\delta_2 - \gamma_2\delta_1}\begin{bmatrix} \delta_2 & -\delta_1 \\ -\gamma_2 & \gamma_1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = M1\begin{bmatrix} x_1 \\ x_2 \end{bmatrix},$$

then:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{\gamma_1\delta_2 - \gamma_2\delta_1}\begin{bmatrix} \alpha_1\delta_2 - \alpha_2\delta_1 & \beta_1\delta_2 - \beta_2\delta_1 \\ -\alpha_1\gamma_2 + \alpha_2\gamma_1 & -\beta_1\gamma_2 + \beta_2\gamma_1 \end{bmatrix}\begin{bmatrix} x_{in} \\ \theta_{in} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$
$$= \begin{bmatrix} M3A & M3B \\ M3C & M3D \end{bmatrix}\begin{bmatrix} x_{in} \\ \theta_{in} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

and one can control u with θ_1 with no interference from θ_2. Similarly, one can control v with θ_2 with no interference from θ_1. Hence u, v are two virtual variables with no cross coupling for control by two steering mirrors.

[0013] The equations above correspond to the control system block diagram shown in Fig. 2. The control system of Fig. 2 receives as input the beam parameters x_{in}, θ_{in}. This control system may be conventionally embodied in analog electronic circuitry or digitally by a conventionally programmed microprocessor or microcontroller. Programming such a device is routine in light of this disclosure. Each block or node in Fig. 2 represents a function with the nodes being summing nodes. The control output signals θ_1 and θ_2 are conventionally transmitted by the control system to drive the steering mirror actuators, thus providing closed-loop feedback control. For control loop gains $G_u(s)$ and $G_v(s)$ much greater than one, $u = v \approx 0$ and $x_{out} = \theta_{out} \approx 0$ for any x_{in} and θ_{in}.

[0014] In another embodiment, the control loop is implemented using the following method. The reflecting mirror angle changes required to correct for the error in beam position are given by:

$$\begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \end{bmatrix} = -M1 \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} u_{offset} \\ v_{offset} \end{bmatrix},$$

where the offset (setpoint) values are given by:

$$\begin{bmatrix} u_{offset} \\ v_{offset} \end{bmatrix} = \frac{1}{2A} \begin{bmatrix} -1 & B+H \\ 1 & A+B+H \end{bmatrix} \begin{bmatrix} x_{offset} \\ \theta_{offset} \end{bmatrix},$$

where x_{offset} and θ_{offset} are the desired beam position and pointing at the output plane. The maximum values of these offsets will be limited by the detectors' usable sensing range. The mirror R1, and R2 angle changes (tilt) are converted into an estimated number of actuator driving pulses as given by $P\# = kL\,\Delta\theta/k\#$, where kL is a global gain constant that is used to speed up or slow down the loop, # is a placeholder for the appropriate actuator, and $k\#$ is that actuator's gain constant relating the actuator position to the signal applied to the actuator driver.

[0015] The main sources of error in this beam sampling system are for example: shot- and Johnson-noise of the position-sensitive detectors Det1, Det2, quantization error in the conventional analog to digital converter (not shown) used to digitize the detectors' output signals, physical misalignment of the beam sampling system as temperature changes, and the smallest incremental motion of the actuators A1, A2 which are driving mirrors R1, R2. All of these error sources can be easily referred back to x_1 and x_2 where they will be injected into the u and v summing nodes with gains:

$$\frac{du}{dx_1}=\frac{1}{2A}\frac{B-T+D+F+(1+M_2)(f_2-A-B+T-D-F)}{M_2f_1-M_1f_2+M_1M_2(f_1-f_2+F)},$$
$$\frac{du}{dx_2}=-\frac{1}{2A}\frac{B-T+D+(1+M_1)(f_1-A-B+T-D)}{M_2f_1-M_1f_2+M_1M_2(f_1-f_2+F)},$$
$$\frac{dv}{dx_1}=-\frac{1}{2A}\frac{A+B-T+D+F+(1+M_2)(f_2-A-B+T-D-F)}{M_2f_1-M_1f_2+M_1M_2(f_1-f_2+F)},$$
$$\frac{dv}{dx_2}=\frac{1}{2A}\frac{A+B-T+D+(1+M_1)(f_1-A-B+T-D)}{M_2f_1-M_1f_2+M_1M_2(f_1-f_2+F)}.$$

[0016] Assuming equal and independent fluctuation in x_1 and x_2, δx, the fluctuations in the output beam position and angle, δx_{out} and $\delta\theta_{out}$, are given by: .

$$\delta x_{out}=2\sqrt{\left[(A+B-T)\frac{du}{dx_1}+(B-T)\frac{dv}{dx_1}\right]^2+\left[(A+B-T)\frac{du}{dx_2}+(B-T)\frac{dv}{dx_2}\right]^2}\,\delta x,$$
$$\delta\theta_{out}=2\sqrt{\left[\frac{du}{dx_1}+\frac{dv}{dx_1}\right]^2+\left[\frac{du}{dx_2}+\frac{dv}{dx_2}\right]^2}\,\delta x.$$

[0017] The actuators' A1, A2 minimum step size, δz_{pico} leads to an output error given by:

$$\delta x_{out}=2(A+B-T)\frac{\delta z_{pico}}{d_{MM}},$$
$$\delta\theta_{out}=2\sqrt{2}\frac{\delta z_{pico}}{d_{MM}},$$

where d_{MM} is the lever arm between the actuator's screw and the center of the optic. The actuators are, e.g., screw driven such as the Picomotor™, a piezoelectric actuator sold by New Focus Inc. Finally, the output is sensitive to twisting and translation of components BS1, BS2, R3, L1, L2, Detl, and Det2. Assuming a uniform temperature of the beam sampling system, these errors will be negligible. The beam does, however, translate a distance d_{BS} by passing through each of beam splitters BS1 and BS2 given by:

$$d_{BS}=t_{BS}\sin\phi\left(1-\frac{\cos\phi\sin\phi}{n_{FS}\sqrt{n_{FS}^2-\sin^2\phi}}\right),$$

where t_{BS} is the thickness of each beamsplitter, ϕ is the beam angle of incidence, and n_{FS} is the index of refraction of the material of the beam splitters. This translation changes as the ambient temperature changes by:

$$\frac{dd_{BS}}{dT} = d_{BS}\alpha_{FS} + \frac{t_{BS}\cos\phi\sin^2\phi}{\sqrt{n_{FS}^2 - \sin^2\phi}}\left(\frac{1}{n_{FS}^2} + \frac{1}{n_{FS}^2 - \sin^2\phi}\right)\frac{dn_{FS}}{dT},$$

where α_{FS} is the thermal expansion coefficient of the material of the beam splitters, leading to an error of:

$$\delta x_{out} = \left[1 + 2(A + B - T)\frac{du}{dx_2} + 2(B - T)\frac{dv}{dx_2}\right]\frac{dd_{BS}}{dT}\Delta T,$$

$$\delta\theta_{out} = 2\left(\frac{du}{dx_2} + \frac{dv}{dx_2}\right)\frac{dd_{BS}}{dT}\Delta T.$$

for a peak system temperature change ΔT.

[0018] The matrix transformation that relates x_1 and x_2 to u and v can be set at the time of manufacture of the system, but even small variations in assembly will introduce large cross coupling between the feedback loops. Therefore, an *in situ* calibration procedure may be used but is not required. Calibration begins by zeroing both x_1 and x_2 (or at least verifying that the beam is in the linear range of the position detectors Det1, Det2), and applying a given angle change to each steering mirror R1, R2 respectively, $\Delta\theta_1$ and $\Delta\theta_2$. The control system will record four quantities: Δx_{11} the change in x_1 due to a change in θ_1, Δx_{21} the change in x_2 due to a change in θ_1, Δx_{12} the change in x_1 due to a change in θ_2, Δx_{22} the change in x_2 due to a change in θ_2. Now the calibration matrix can be computed by noting that:

$$\gamma_1 = \frac{\Delta x_{11}}{\Delta\theta_1},$$

$$\delta_1 = \frac{\Delta x_{12}}{\Delta\theta_2},$$

$$\gamma_2 = \frac{\Delta x_{21}}{\Delta\theta_1},$$

$$\delta_2 = \frac{\Delta x_{22}}{\Delta\theta_2},$$

and as above:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{\gamma_1\delta_2 - \gamma_2\delta_1}\begin{bmatrix} \delta_2 & -\delta_1 \\ -\gamma_2 & \gamma_1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$$

[0019] The calibration process can incorporate filtering, *i.e.* changing the angles multiple times and averaging the results, and recursion, *i.e.* using the feedback loop to zero u and v in between calibration attempts.

[0020] Once the system is installed and aligned, and with the position and angle offsets set to zero, the output beam will be driven toward the optical axis, $x_{out} = \theta_{out} = 0$. The optical axis is defined by the physical position of the detectors Det1, Det2, as imaged by the lenses L1, L2, and is shown in Fig. 3. Fig. 3 shows the optical axis is defined as the line running through the image of each of the two detectors' centers, I_1 and I_2. Given an alignment tolerance Δx_{align} on the relative position of the lenses and detectors, the position of the beam images will be displaced by $\Delta I_1 = \Delta x_{align}/M$ and $\Delta I_2 = \Delta x_{align}/M$, where it is assumed that magnification $M = M_1 = M_2$. These displacements will lead to a maximum position and angle variation at the output plane, Δx_{axis} and $\Delta\theta_{axis}$, given by:

$$\Delta x_{axis} = \frac{\Delta x_{align}}{M} - \left[A + B + C - f_1\left(1 + \frac{1}{M}\right)\right]\Delta\theta_{axis},$$

$$\Delta\theta_{axis} = -\frac{2\Delta x_{align}}{(1+M)(f_1 - f_2)}.$$

[0021] The present system and control signal processing result in two independent feedback loops that meet high performance requirements. The above field calibration can be performed after installation and periodically thereafter.

[0022] This disclosure covers control in two axes (one axis on each of two steering mirrors). The process underlying the third and fourth axes of a beam pointing and translation system (the second axis on each of the two steering mirrors) is identical. The overall effect is to generate two simultaneous control loops for *u1,v1* and *u2,v2* for both of the tip-tilt axes of the steering mirrors. In this disclosure the actuators A1, A2 are shown as being arranged to be in parallel, but this is not limiting. The above calibration process and/or software control of the actuators can be employed to map the actuators (two, or four including those for the second axis of the steering mirrors) to each of the four control variables *u1, v1* and *u2, v2*.

[0023] This disclosure is illustrative but not limiting; further modifications will be apparent to one skilled in the art in light of this disclosure and are intended to fall within the scope of the appended claims.

CLAIMS

1. Apparatus comprising:

a first steering reflector on which a beam of light is incident;

a second steering reflector on which light reflected from the first steering reflector is incident;

a first beam splitter on which light reflected from the second steering reflector is incident;

a second beam splitter on which light reflected from the first beam splitter is incident;

a first detector on which light reflected from the first beam splitter is incident; and

a second detector on which light transmitted by the second beam splitter is incident;

wherein a first value which is a function of an output signal of both detectors is indicative of a state of the first steering reflector, and a second value which is a function of an output signal of both detectors is indicative of a state of the second steering reflector.

2. The apparatus of Claim 1, further comprising a controller coupled between the detectors and the steering reflectors, whereby the controller changes a state of the first and second steering reflectors responsive to respectively the first and second values.

3. The apparatus of Claim 1, each steering reflector including a reflector coupled to an actuator.

4. The apparatus of Claim 3, each steering reflector having a second actuator coupled to the reflector to tilt the reflector in a direction substantly orthogonal to a direction in which the first actuator tilts that reflector.

5. The apparatus of Claim 1, wherein light transmitted by the first beam splitter is directed out of the apparatus.

6. The apparatus of Claim 1, further comprising a third reflector positioned to reflect the light transmitted by the second beam splitter to the second detector.

7. The apparatus of Claim 2, the controller including two control loops, one control loop being associated with each of the first and second values.

8. The apparatus of Claim 1, wherein each of the first and second values is a function of a displacement and an angle of the light beam incident on the apparatus.

9. The apparatus of Claim 2, wherein the controller includes means for calibrating the apparatus.

10. The method of Claim 1, further comparing a first lens located to focus light onto the first detector and a second lens located to focus light onto the second detector.

11. Method for operating an optical apparatus having two steering reflectors, comparing the acts of:

splitting light reflected serially from the two steering reflectors;

splitting the split light, into two portions;

detecting a first portion of the twice split light;

detecting a second portion of the twice split light;

obtaining a first value which is a function of an output signal from both acts of detecting, the first value being indicative of a state of the first steering reflector; and

obtaining a second value which is a function of an output signal from both acts of detecting, the second value being indicative of a state of the second steering reflector.

12. The method of Claim 11, further comprising the act of:

controlling a state of the first and second steering reflectors responsive to respectively the first and second values.

13. The method of Claim 11, further comprising the act of changing the state of each steering reflector by an actuator.

14. The method of Claim 13, further comprising the act of providing a second actuator associated with each steering reflector to tilt the steering reflector in a direction orthogonal to a direction in which the first actuator tilts that reflector.

15. The method of Claim 11, further comprising the act of directing externally a portion of the light which is split from the first act of splitting.

16. The method of Claim 11, further comprising the act of reflecting the second portion of the twice split light prior to the act of detecting same.

17. The method of Claim 12, the controlling including:

providing two control loops, one control loop being associated with each of the first and second values.

18. The method of Claim 11, wherein each of the first and second values is a function of a displacement and an angle of light incident on a first of the steering reflectors.

19. The method of Claim 11, further comprising the act of calibrating the optical apparatus.

20. The method of Claim 11, further comprising the act of focusing the light prior to detecting same.

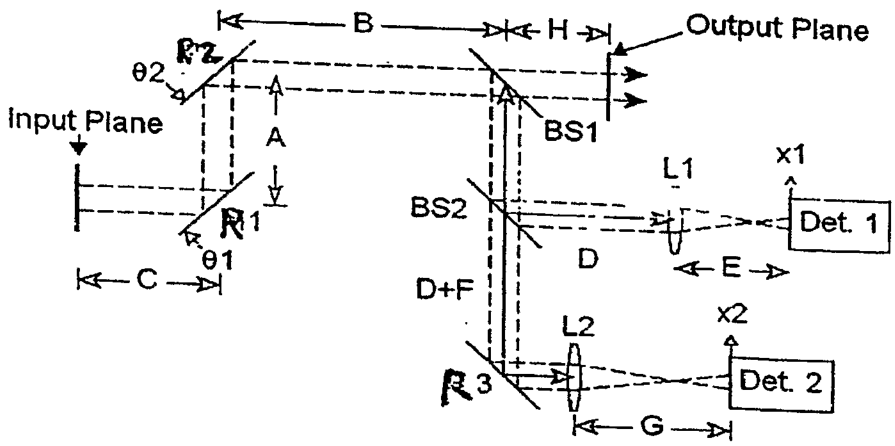
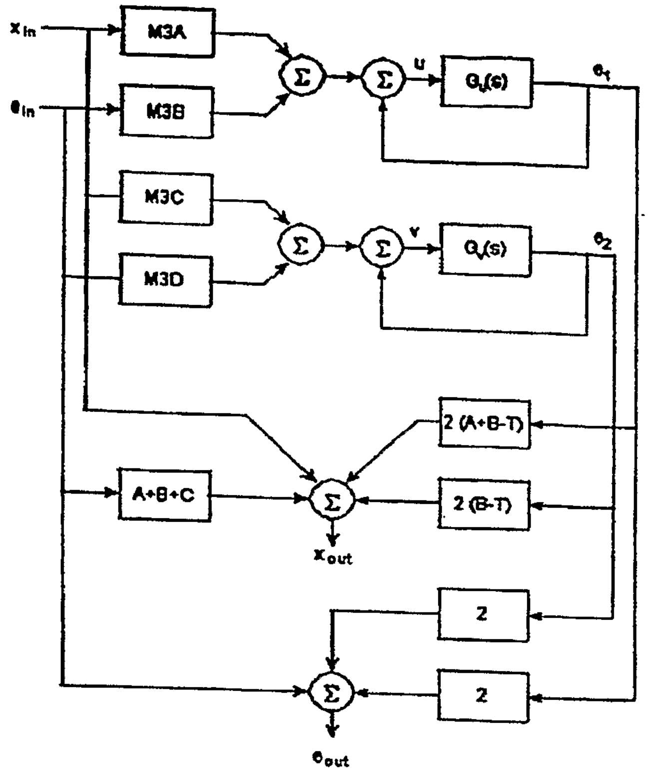

B
H
Output Plane
R2
θ2
Input Plane
A
BS1
L1
x1
BS2
R1
Det. 1
θ1
D
E
C
D+F
L2
x2
R3
Det. 2
G

Figure 1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e in
M3A
M3B
M3C
M3D
Σ
u
v
Gu(s)
Gv(s)
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e2
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A+B+C
2 (B-T)
x out
2
2
e out

Figure 2

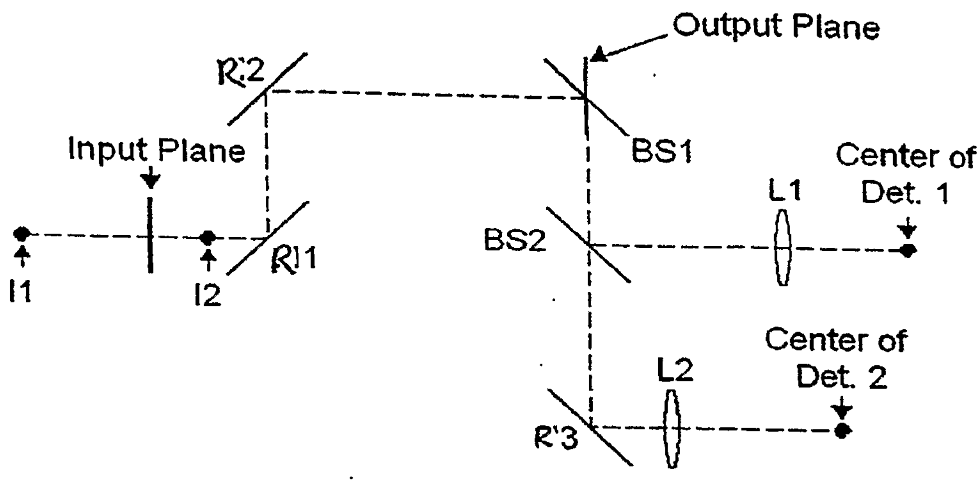
Output Plane
R2
BS1
Input Plane
Center of
Det. 1
L1
BS2
R1
I1
I2
Center of
Det. 2
L2
R3

Figure 3.