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(54) Title: HIGH-DENSITY SPATIAL LIGHT MODULATOR
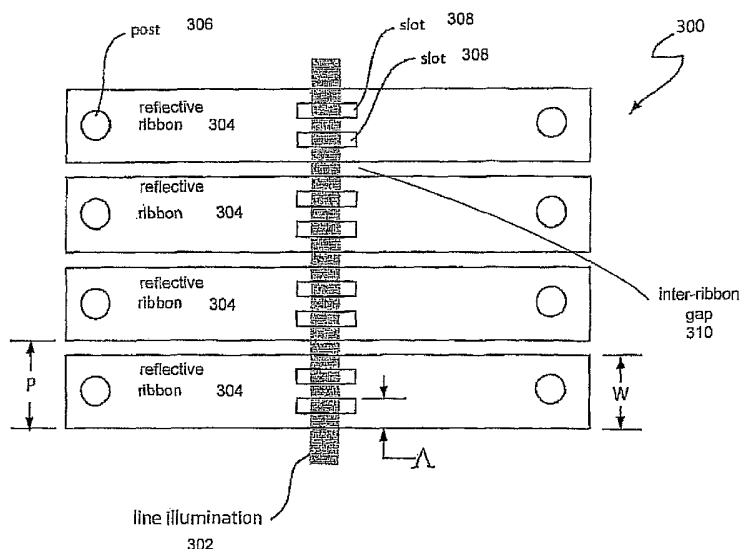
(57) Abstract: In one embodiment, a high-density spatial light modulator (300) includes a substrate (402) having a reflective surface (404) and a reflective ribbon (304) over the reflective surface. The ribbon (304) may have one or more openings, such as rectangular slots (308). The openings allow light to pass through the ribbon and impinge on the reflective surface. Deflecting the ribbon (304) towards the substrate (402) thus allows for dynamically-controllable diffraction of incident light. The spatial light modulator pixel requires less space than a conventional light modulator, thus allowing for relatively large pixel count within a manufacturable device size. Other embodiments are also disclosed.

SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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HIGH-DENSITY SPATIAL LIGHT MODULATOR

Inventors: Jahja I. Trisnadi and Clinton B. Carlisle

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CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. provisional application

no. 60/506,624, entitled "Spatial light modulator," filed September 26, 2003, by

inventors Jahja I. Trisnadi and Clinton B. Carlisle. The disclosure of the

10   aforementioned U.S. provisional application is hereby incorporated by reference

in its entirety.

BACKGROUND OF THE INVENTION

1.   Field Of The Invention

The present invention relates generally to light modulators, and more

15   particularly but not exclusively to micro electromechanical system (MEMS)

based spatial light modulators.

2.   Description Of The Background Art

Spatial Light modulators fabricated using micro electromechanical system

(MEMS) technology, in general, are well known. Examples of such light

20   modulators include the Grating Light Valve™ (GLV™) light modulator available

from Silicon Light Machines Corporation of Sunnyvale, California. Devices that

are of the same type as GLV™ light modulators are hereinafter referred to as

"ribbon light modulators". Ribbon light modulators are described in the following

disclosures, which are integral to this provisional application and can be found in

the following patents: U.S. Patent No. 5,311,360, entitled "Method and

Apparatus for Modulating a Light Beam" to Bloom et al.; U.S. Patent No.

5,841,579, entitled "Flat Diffraction Grating Light Valve" to Bloom et al.; U.S.

Patent No. 5,661,592, "Method of Making and an Apparatus for a Flat Diffraction

5   Grating Light Valve" to Bornstein et al.; and U.S. Patent No. 6,215,579, entitled

"Method and Apparatus for Modulating an Incident Beam for Forming a Two-

Dimensional Image" to Bloom et al. The aforementioned four U.S. Patents are

hereby incorporated by reference. Ribbon light modulators can be employed in

various applications including optical networks, video, and printing.

10   FIGS. 1 and 2 show schematic diagrams of conventional ribbon light

modulator structures. In FIG. 1, each ribbon **102** with reflective layer **103** is

electro-statically deflectable towards the substrate **104**, with reflective layer **106**

thereon, to form a diffraction grating with adjustable diffraction strength. In FIG.

2, active deflectable ribbons **202** are interlaced with static un-deflectable ribbons

15   **204** also to form an addressable diffraction grating with adjustable diffraction

strength. In FIG. 2, the substrate **208** need not have a reflective surface layer.

A ribbon **102** and a gap **108** (ribbon-gap) pair **110** in FIG. 1 or an active ribbon

202 and a static ribbon **204** (ribbon-ribbon) pair **206** in FIG. 2 constitutes a

diffraction period. One or more periods can be addressed as a "pixel." A pixel

20   can be addressed to modulate incident light by diffraction. Thus, a pixel can be

used to display or print a unit of an image, for example.

While conventional spatial light modulators can be satisfactorily used in a

wide variety of high resolution applications, there are emerging applications that

may require even higher pixel resolution. Examples of these emerging

applications include super high resolution display, maskless lithography, high

resolution printing for printed circuit boards and flat panel displays, and a host of

other applications. There are also existing applications, such as laser printers,

that can be considerably improved by the use of high resolution spatial light

5   modulators.

SUMMARY

In one embodiment, a high-density spatial light modulator includes a

substrate having a reflective surface and a reflective ribbon over the reflective

surface. The ribbon may have one or more openings, such as rectangular slots.

10   The openings allow light to pass through the ribbon and impinge on the reflective

surface. Deflecting the ribbon towards the substrate thus allows for dynamically-

controllable diffraction of incident light. The spatial light modulator pixel requires

less space than a conventional light modulator, thus allowing for relatively large

pixel count.

15   These and other features of the present invention will be readily apparent

to persons of ordinary skill in the art upon reading the entirety of this disclosure,

which includes the accompanying drawings and claims.

DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically shows a conventional ribbon light modulator

20   structure.

FIG. 2 schematically shows another conventional ribbon light modulator

structure.

FIG. 3 schematically shows a top view of a high-density ribbon light

modulator in accordance with an embodiment of the present invention.

FIG. 4 schematically shows a center cross-section of the ribbon light

modulator of FIG. 3.

5   The use of the same reference label in different drawings indicates the

same or like components. Drawings are not necessarily to scale unless

otherwise noted.

DETAILED DESCRIPTION

In the present disclosure, numerous specific details are provided such as

10   examples of apparatus, components, and methods to provide a thorough

understanding of embodiments of the invention. Persons of ordinary skill in the

art will recognize, however, that the invention can be practiced without one or

more of the specific details. In other instances, well-known details are not shown

or described to avoid obscuring aspects of the invention.

15   The present invention relates to a diffractive, spatial light modulator.

While embodiments of the invention are described using linear ribbon light

modulators as examples, it should be understood that the invention is not so

limited and may also be employed in other types of spatial light modulators.

FIGS. 3 and 4 show schematic diagrams of a high-density or high pixel

20   count linear, diffractive, spatial ribbon light modulator **300** in accordance with an

embodiment of the present invention. FIG. 3 shows a top view of an

embodiment of the light modulator **300**, while FIG. 4 shows a cross-sectional

view of the embodiment of the light modulator **300** as seen by cutting through the

line illumination **302** denoted in FIG. 3. Light modulator **300** may have from a few to many thousands, or more, reflective ribbons, but only four ribbons **304** are shown for clarity of illustration. The ends of each ribbon **304** may be anchored using posts **306** or other means. The ribbons **304** and the substrate beneath

5   them preferably have reflective top surfaces and are separated by an air gap. In the example of FIG. 4, the top surface of the substrate **402** is shown as having an overlying reflective layer **404**. Each ribbon **304** preferably also has such a reflective layer on its top surface (as illustrated in FIGS. 1 and 2). Each ribbon has one or more openings in the form of rectangular slots **308**. The slots **308**

10   allow portions of light illuminating the shaded region labeled "line illumination" to impinge on the reflective layer **404** of the substrate **402** underneath the ribbons **304**. In a preferred embodiment, the spatial light modulator **300** is configured such that a) the area-reflectivity product due to the reflective layer on the ribbons, and b) the area-reflectivity product due to the openings within and

15   between the ribbons, are approximately equal. Light modulator **300** may be fabricated using a MEMS process technology similar to those employed in the fabrication of conventional ribbon light modulators.

The middle portions (in between the anchored portions) of the reflective ribbons **304** may be deflected towards the substrate by electrostatic force, for

20   example. Deflecting the ribbons **304** varies the distance between the top surfaces of the ribbons **304** and the reflective layer **404** of the substrate **402**, thereby varying the path length difference of light impinging on them. This allows incident light to be modulated by diffraction.

In light modulator **300**, a diffraction period "Λ" comprises a strip of ribbon surface and an opening. An addressable pixel "P" has "N" periods/pixel (i.e., P=NΛ). In the example of FIGS. 3 and 4, each pixel has three periods. Note that the gaps **310** between ribbons have the same effect as the slots **308**. The

5   ribbon width "W" is thus given by the equation W = P-(Λ / 2). Light modulator **300** may be operated in zero-order or first-order mode. In zero-order mode, the 0th order components of the light are collected and modulation is obtained by diffracting the light away into first and higher orders. In the first-order mode, it is the modulated 1st order components of the light that are collected. However,

10   since the period of light modulator **300** may be just a few wavelengths, the diffraction angle may get very large. Therefore, it is preferable to operate light modulator **300** in the zero-order mode.

The distance "H" is the distance between the top reflective surfaces of the ribbons and the reflective layer of substrate. If H = (odd integer)(λ / 4), where "λ"

15   is the wavelength of the incident light, then the light modulator **300** is normally OFF. In other words, the un-deflected state is diffracting so light is discarded, corresponding to a dark pixel in the zero-order mode. If H = (even integer)(λ / 4), then the light modulator **300** is normally ON. That is, the un-deflected state is specular, which corresponds to a bright pixel in the zero-order mode. Because a

20   ribbon may snap down if the deflection exceeds H/3, the smallest even and odd integer multipliers are preferably four and five, respectively. A height margin δ may be added to the distance H to allow for uniformity calibration. In other words , a light modulator **300** that is normally OFF may be configured with H = M(λ / 4)+δ, where M is an odd integer no less than five (i.e., M = 5, or 7, or 9, or

11 etc.), while a light modulator 300 that is normally ON may be configured with

$H = M(\lambda / 4)+\delta$, where M is an even integer no less than four (i.e., M = 4, or 6, or

6, or 10 etc.).

As a specific example, Λ = 1 micrometer (μm) and N = 3 periods/pixel

5   result in

P = 3 μm (i.e., 1μm x 3). The slot width as well as the gap between ribbons are

each equal to $(\Lambda / 2)$ or 0.5 μm (i.e., 1 μm / 2). The ribbon width W is 2.5 μm

(i.e., 3 μm - (1 μm / 2)). For a light source having a wavelength λ = 0.5 μm, a

normally OFF light modulator may have a distance H of 0.625 μm (odd integer =

10   5) or 0.875 μm (odd integer = 7). For ten thousand (10,000) pixels, the die will

be only about 30 mm (10,000 x 3 μm) long.

For ribbon structures that are $\sim\lambda$, full vector diffraction analysis may be

employed to optimize the device operation and account for polarization effects in

the light field interaction with the structure. Also, the drive electronics for each

15   pixel may be integrated in the same silicon as the ribbon structure to allow for

very high pixel count and fine pixel pitch.

A large pixel count, diffractive, spatial light modulator has been disclosed.

The modulator may configured as a linear array, or alternatively, as a two-

dimensional array. While specific embodiments have been provided, it is to be

20   understood that these embodiments are for illustration purposes and not limiting.

Many additional embodiments will be apparent to persons of ordinary skill in the

art reading this disclosure.

CLAIMS

What is claimed is:

1.   A MEMS spatial light modulator comprising:

        a substrate having a reflective surface;

5   a ribbon over the reflective surface, the ribbon having a reflective surface

and also having one or more openings in a middle portion to allow light to pass

through and impinge on the reflective surface; and

        wherein the ribbon is deflectable towards the substrate to diffract incident

light in a controllable manner.

10

2.   The light modulator of claim 1, wherein the ribbon is deflectable using

electrostatic force.

3.   The light modulator of claim 1, wherein the light modulator is configured to

15   controllably deflect the ribbon by approximately one quarter wavelength of the

light.

4.   The light modulator of claim 1, further comprising a second ribbon that is

deflectable towards the reflective surface.

20

5.   The light modulator of claim 4, wherein a gap between the two ribbons has a same distance as a width of an opening in the ribbon.

6.   The light modulator of claim 1, wherein each opening comprises a slot.

5

7.   The light modulator of claim 6, wherein the slot is substantially rectangular in shape.

8.   The light modulator of claim 1, wherein a width of each opening is equal

10   to a distance between two openings.

9.   The light modulator of claim 1, wherein the ribbon is controlled so as to represent a single pixel.

15   10.   The light modulator of claim 1, wherein an undeflected height of the ribbon is approximately equal to one fourth a wavelength of the light multiplied by an integer.

11.   The light modulator of claim 10, wherein the integer is at least a minimum

20   number to avoid a snap down condition of the ribbon when the ribbon is deflected.

12.   The light modulator of claim 11, wherein the minimum number is four.

13.   The light modulator of claim 10, wherein the integer is odd, and wherein

5   the light is diffracted when the ribbon is undeflected.

14.   The light modulator of claim 10, wherein the integer is even, and wherein

the light is specularly reflected when the ribbon is undeflected.

10   15.   A high-density spatial light modulator comprising:

a substrate;

an array of deflectable ribbon devices configured above the substrate;

one or more openings within each ribbon device;

an opening between adjacent ribbon devices;

15   a reflective layer on each ribbon device,

a reflective layer on the substrate configured at least beneath said

openings; and

wherein the spatial light modulator is configured such that area-reflectivity

products of a) the reflective layer on the ribbons and b) the openings within and

20   between the ribbons, are approximately equal.

16.   The spatial light modulator of claim 15, wherein the array comprises a

linear array.

17.   The spatial light modulator of claim 15, wherein the array comprises a

5   two-dimensional array.

18.   The spatial light modulator of claim 16, wherein a periodicity of ribbon

devices in the linear array is one ribbon device per three micrometers or less.

10   19.   The spatial light modulator of claim 16, wherein the array includes 10,000

ribbon devices or more within a single die, wherein each ribbon device

corresponds to a controllable pixel.

20.   A method of spatially modulating light, the method comprising:

impinging light of a wavelength upon an array of ribbon devices over a

15   substrate; and

controllably deflecting the ribbon devices,

wherein the substrate comprises a reflective surface, and

wherein each ribbon device comprises a reflective surface and further

comprises one or more openings in a middle portion to allow light to pass

20   through.

21.   The method of claim 20, wherein at least a single ribbon device
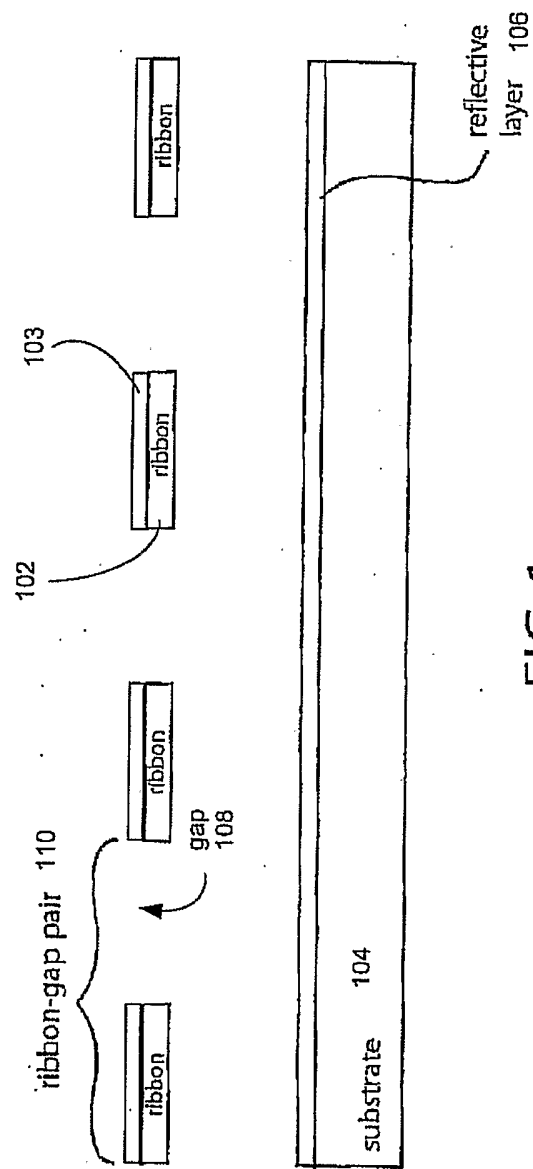
corresponds to an individually controllable pixel.
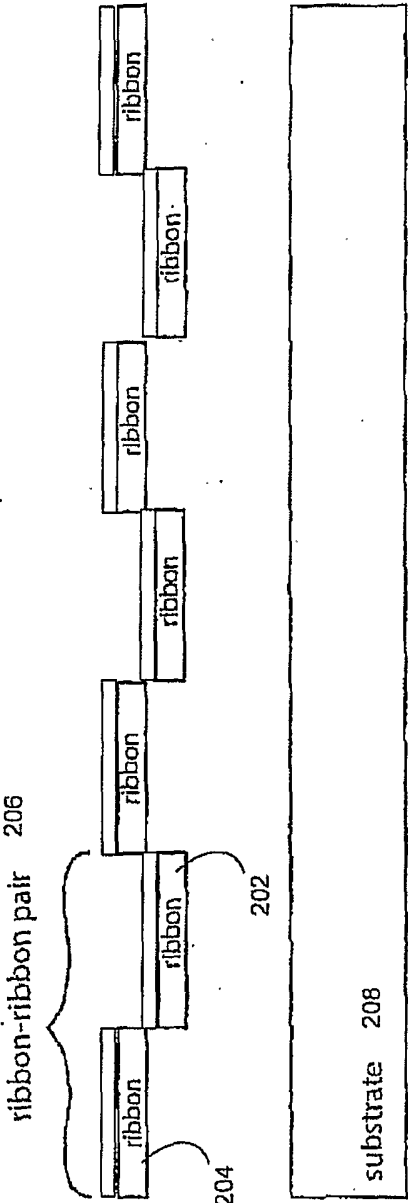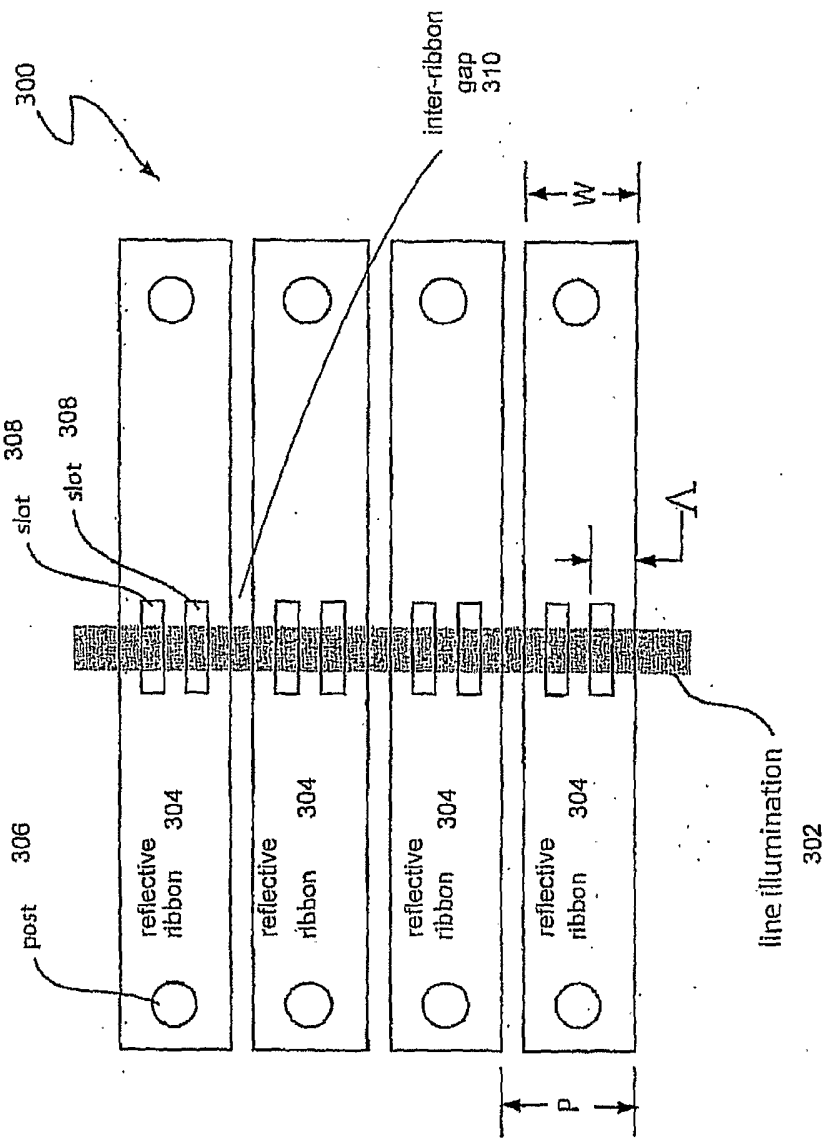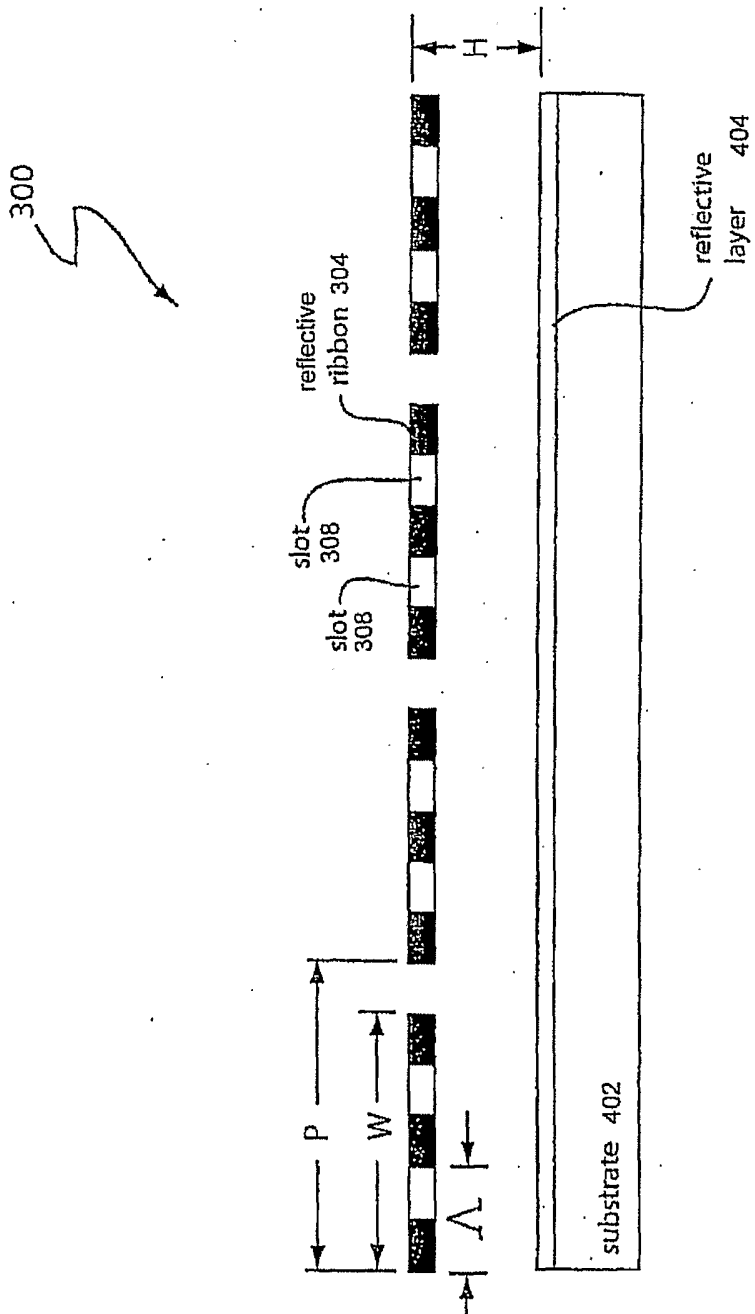
FIG.1
(BACKGROUND ART)

FIG. 2
(BACKGROUND ART)

FIG.3

4/4

FIG.4