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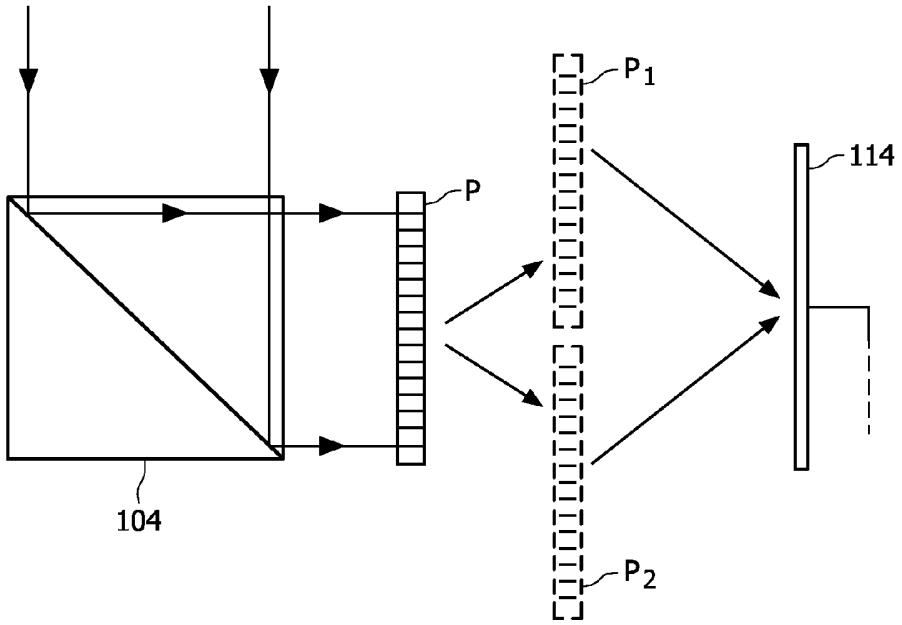
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(54) **Title:** MEDHOD FOR READING-OUT PHASE-MODULATION RECORDED DATA IN A HOLOGRAPHIC MEDIUM



(57) **Abstract:** The invention relates to a method for reading-out data recorded in a holographic medium (106) as a phase-modulated pattern of data pixels. The method comprises the steps of reconstructing said phase-modulated pattern (P), duplicating said reconstructed phase- modulated pattern in a first reconstructed phase-modulated pattern (Pl) and a second phase- modulated pattern (P2) shifted from said first reconstructed phase-modulated pattern by an integer number of data pixels, and having interfere said first and second reconstructed phase- modulated patterns.

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METHOD FOR READING-OUT PHASE-MODULATION RECORDED DATA IN A HOLOGRAPHIC MEDIUM

FIELD OF THE INVENTION

The present invention relates to a method for reading-out data recorded in a holographic medium as a phase-modulated pattern of data pixels and to a device for reading-out such data.

BACKGROUND OF THE INVENTION

In holographic data storage systems, several methods have been proposed to encode the data, mostly by using a two-dimensional (2D) amplitude-modulated pattern of data pixels, which is encoded and stored in a holographic medium by interference with an unmodulated reference beam.

Read-out of the data is done by illuminating the inscribed holographic medium in the same way as it was recorded, hence leading to the reconstruction of the amplitude-modulated pattern. Detection is performed by measuring the intensity pattern on a 2D detector and processing the data.

In order to increase the data capacity storage of the holographic medium used in holographic data storage systems, a solution consists in carrying out multiplexing so as to get as many holographic patterns as multiplexing channels.

Multiplexing can be achieved by using various methods.

One method is called “angle multiplexing”. According to this method, the angle of the reference beam with respect to the recording medium is varied so that a plurality of holograms is recorded at a same location of the recording medium, each corresponding to a given angle of the reference beam.

In “wavelength multiplexing”, the wavelength of the radiation beam is tuned in order to record different holograms at the same location of the holographic medium.

“Shift multiplexing” consists in recording a set of holograms by shifting the recording medium with respect to the optical unit. Once a hologram has been recorded at a given location of the recording medium, the recording medium is shifted over a distance that is less that the width of the hologram. Shift multiplexing is only possible when spherical waves interfere.

Naturally, combinations of different multiplexing methods may be possible.

However, although multiplexing leads to good results, it is still desirable to obtain an even higher storage capacity of the holographic recording medium, namely by providing methods alternative to the known method involving amplitude-modulation.

To this end, Figure 1 shows a holographic recording device making use of phase-modulation.

The holographic device comprises a radiation source 100, a collimator 101, a first beam splitter 102, a phase-modulation spatial light modulator 201, a second beam splitter 104, a lens 105, a first deflector 107 and a first telescope 108. The holographic device is intended to record data in the holographic medium 106.

The recording of data in the holographic medium 106 is similar to the recording using amplitude-modulation, except that the signal beam is modulated in phase instead of being modulated in amplitude. Therefore, the amplitude modulation spatial light modulator is replaced with the phase modulation spatial light modulator 201 which comprises an array of modulation elements corresponding to data pixels. At least some modulation elements are adapted for modifying the phase of the portion of the signal beam that passes through these modulation elements.

For example, a first modulation element has a first refractive index n1 and a second modulation element a second refractive index n2, where n1 is different from n2. The first and second refractive index n1 and n2, respectively, are such that a phase difference between the two portions of the radiation beam exiting the spatial light modulator is created. For instance, a phase difference of π may be created between these two portions of the radiation beam beyond the phase modulation spatial light modulator 201.

It is thus possible to encode data by means of the phase modulation spatial light modulator 201. The phase modulation spatial light modulator 201 may generate only two different phases, such as 0 and p, but may also generate more than two different phases. To this end, the refractive indices of the modulation elements of the phase modulation spatial light modulator 201 can take more than two different values. An example of phase modulation spatial light modulator 201 is a liquid crystal device comprising an array of liquid crystal pixels. The refractive index of each pixel may be controlled by a voltage applied between electrodes in each pixel. Data are sent to the phase modulation spatial light modulator 201 and the suitable voltages are applied to the liquid crystal pixels so as to encode the data in the signal beam.

Figure 2 illustrates another holographic recording device comprising the same elements as the holographic device of Figure 1, except that it further comprises an amplitude-

modulation spatial light modulator 103. The signal beam is thus modulated in phase and in amplitude. This allows recording at a same location of the holographic medium 106 with a same multiplexing parameter. Hence, it is possible to record more information than in the prior art at a same location of the recording medium 106.

Figure 3 illustrates a holographic read-out device comprising the radiation source 100, the collimator 101, the first beam splitter 102, the phase modulation spatial light modulator 201, the second beam splitter 104, the lens 105, the first mirror 109, the half wave plate 110, the second mirror 111, the second deflector 112, the second telescope 113, the detector 114, a third beam splitter 401, deflection means such as a grating 402 intended to direct a probe signal towards the detector 114 so as to interfere with the reconstructed signal beam before the latter reaches the detector 114.

During read-out, the signal beam generated by means of the first beam splitter 102 is blocked for example by inserting a mechanical beamstop, e.g. a diaphragm or the like (not represented in Figure 3), and a reconstructed phase-modulated pattern is generated, which corresponds to the data recorded. The wavefront of the reconstructed pattern equals the wavefront of the phase modulation spatial light modulator 201 that was used for recording said data page. As the reconstructed signal beam and the probe signal beam interfere before reaching the detector 114, this gives rise to a detected signal beam, which wavefront is the sum of the wavefronts of the reconstructed signal beam and the probe signal beam.

It will be appreciated that the use of phase-modulation requires the reconstructed phase-modulated pattern to interfere with a probe signal beam thus leading to an intensity-modulated beam which can be detected by the detector 114 in the conventional way.

However, this implies a rather complicated optical device, as shown on Figure 3, which is difficult to align and miniaturise owing to the presence of a probe branch including the third beam-splitter 401 and the grating 402.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a method and a device for reading-out phase-modulated data in a holographic storage medium which would be simpler to carry out than the known solution.

To this end, the invention proposes a method for reading-out data recorded in a holographic medium as a phase-modulated pattern of data pixels, comprising the steps of reconstructing said phase-modulated pattern, duplicating said reconstructed phase-modulated pattern in a first reconstructed phase-modulated pattern and a second phase-modulated

pattern shifted from said first reconstructed phase-modulated pattern by an integer number of data pixels, and having interfere said first and second reconstructed phase-modulated patterns.

It can be readily understood that this proposed method does not need any further probe beam since the required conversion of the reconstructed phase-modulated pattern into an intensity-modulated pattern is achieved by interfering two duplicated reconstructed phase-modulated patterns provided that one duplicated pattern be shifted relative to the other.

In an advantageous embodiment of the invention, said first and second reconstructed phase-modulated patterns are obtained by reflection of said reconstructed phase-modulated pattern on each face of a plane parallel plate.

In order to enhance the contrast of the interference pattern, it is recommended by the invention that the reflection and transmission coefficients of the faces of said plane parallel plate are determined so that the intensities of said first and second reconstructed phase-modulated patterns are substantially equal.

Likewise, the invention provides that the optical path difference between said first and second reconstructed phase-modulated patterns is tuned so as to maximize the interference contrast.

Advantageously, data are also recorded in said holographic medium as an amplitude-modulated pattern of data pixels and an amplitude information is detected so as to compensate for amplitude variations in said reconstructed phase-modulated patterns. In this latter embodiment, said amplitude information is detected from the reconstructed amplitude and phase-modulated pattern transmitted through said plane parallel plate.

The invention also relates to a device for reading-out data recorded in a holographic medium as a phase-modulated pattern of data pixels, having means for duplicating a reconstructed phase-modulated pattern in a first reconstructed phase-modulated pattern and a second phase-modulated pattern shifted from said first reconstructed phase-modulated pattern by an integer number of data pixels, and for having interfere said first and second reconstructed phase-modulated patterns.

Said device is designed so that said duplicating means comprise a plane parallel plate arranged in such a way that a beam from a data pixel of said reconstructed phase-modulated pattern is duplicated in a beam of said first reconstructed phase-modulated pattern by reflection on one face of said plane parallel plate and a beam of said second reconstructed phase-modulated pattern by reflection on an other face of said plane parallel plate.

In order to allow the two reconstructed beams to interfere, the angle of incidence of said beams and the thickness of said plane parallel plate are determined so that a beam of said first reconstructed phase-modulated pattern and a beam of said second reconstructed phase-modulated pattern shifted by an integer number of data pixels are capable of interfering.

These and other aspects of the invention will be apparent from and will be elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in more detail by way of example with reference to the accompanying drawings, in which :

- Figure 1 shows a first embodiment of a holographic recording device in accordance with the prior art.
- Figure 2 shows a second embodiment of a holographic recording device in accordance with the prior art.
- Figure 3 shows a holographic read-out device in accordance with the prior art.
- Figure 4 shows a holographic read-out device in accordance with the invention.
- Figure 5 shows a particular embodiment of the holographic read-out device of Figure 4.
- Figure 6 shows the duplicating means of the embodiment of Figure 5.
- Figure 7 shows a particular embodiment of the duplicating means of Figure 6.
- Figure 8 shows an alternative to the embodiment of Figure 5.

DETAILED DESCRIPTION OF THE INVENTION

In Figure 4 is represented a holographic read-out device intended to read-out a phase-modulated pattern of data pixels recorded in a holographic storage medium 106. This phase-modulated pattern is recorded by use of a recording device similar to that shown in Figure 1. Alternatively, if simultaneous phase and amplitude-modulations are sought, recording of said data pattern may be carried-out by means of the device represented in Figure 2.

The read-out device of Figure 4 is similar to that of Figure 3 except that the branch including the grating 402 is suppressed, thus resulting in the deletion of the third beam splitter 401.

As schematically shown in Figure 4, read-out of the recorded phase-modulated pattern recorded in the holographic medium 106 is achieved by reconstruction of the phase-modulated pattern in the conventional way represented in Figure 3, duplication of said reconstructed pattern P in a first reconstructed phase-modulated pattern P1 and a second

phase-modulated pattern P2 shifted from said first reconstructed phase-modulated pattern by an integer number of data pixels, and interference of said first P1 and second P2 reconstructed phase-modulated patterns, the interference pattern being detected by the detector 114. The signal provided by the detector 114 is then processed so as to retrieve the recorded data.

Figure 5 illustrates a particular embodiment of the device of Figure 4 wherein the first P1 and second P2 reconstructed phase-modulation patterns are obtained by reflection of the initial reconstructed phase-modulated pattern P on each face of plane parallel plate 300 acting as a duplicating means.

As shown in detail in Figure 6, a beam Bi coming from a data pixel pi of the reconstructed phase-modulated pattern P is reflected on the front face 301 of the plate 300 as beam Bi1 and on the back face 302 as beam Bi2. Likewise, a beam Bj coming from a data pixel pj shifted from said data pixel pi by an integer number is reflected as beam Bj1 and beam Bj2 on the front 301 and back 302 faces of the plate 300 respectively. In that case, the first P1 and the second P2 reconstructed phase-modulation patterns respectively consist of the whole beams Bi1, Bj1,... and Bi2, Bj2,...In order to obtain an interference pattern on the detector 114, it is necessary to have interfere beams like Bi2 and Bj1 in the example of Figure 6.

Figure 7 shows an advantageous embodiment for having beams Bi2 and Bj1 interfere. In that embodiment, the angle of incidence i of the beams Bi, Bj,... and the thickness e of the plane parallel plate 300 are determined so that beams Bi2 and Bj1 overlap and thus may interfere. If δ is the distance between pixels pi and pj in the reconstructed phase-modulation pattern P, the angle of incidence i and the thickness e of the plate 300 should verify:

$$2e\sin i = \delta$$

δ can be chosen as the distance between two nearest neighbour data pixels, but it can also be chosen as the distance between next nearest neighbour data pixels, or even further neighbour data pixels, by increasing the angle of incidence i.

The values for the reflection and transmission coefficients of coatings of the faces 301 and 302 of the plane parallel plate 300 may be determined by the condition that the contrast of the interference pattern be maximum, which means that the two beams Bi2 and Bj1 should have substantially equal intensity. This results in the following equation:

$R1=T1*R2*T1$

where R1 and T1 are the reflection and transmission coefficients of the front face 301 and R2 is the reflection coefficient of the back face 302.

In the simple case of R1=1-T1 (no absorption) and R2=1 (full reflection of the back face), one obtains R1=0.382. Of course, other values may be chosen to reduce the influence of ghost-reflections for instance.

The phase difference $\Delta\varphi$ between beams Bi2 and Bj1 of Figure 7 is the sum of phase differences $\Delta\varphi$pixel and $\Delta\varphi$plate where $\Delta\varphi pixel=\varphi i-\varphi j$ is the phase difference of the two data pixels pi and pj, and $\Delta\varphi plate=2\pi(2ne/\cos i)/\lambda-2\pi(\delta tgi)/\lambda$, n being the refraction index of the material the plate 300 is made of.

The intensity of the interference pattern is proportional to:

$1+(\cos\Delta\varphi pixel\cos\Delta\varphi plate-\sin\Delta\varphi pixel\sin\Delta\varphi plate)$

A maximum contrast for the interference pattern is obtained under the condition that $\Delta\varphi$plate equals $k\pi$. This condition is achieved by insertion of a liquid crystal cell in the substrate of the plane parallel plate 300. Upon tuning the voltage across the liquid crystal layer, the refraction index n of the overall plate may be tuned so that the above mentioned condition for maximum contrast is fulfilled.

In that case, the intensity of the interference pattern is given by $1+\cos\Delta\varphi$pixel, leading thus to the determination of the phase difference $\Delta\varphi$pixel and, accordingly, to the transition between the data pixels pi and pj. For example, if data pixels pi and pj are bits 0 or 1 respectively associated with phases $\varphi i=0$ and $\varphi j=\pi$, one can detect transitions between bits 0 and 1. A prior calibration is then necessary to determine the absolute value of the bits.

Figure 8 refers to an embodiment wherein the data are recorded in the holographic medium 106 by means of the device shown in Figure 2 involving a dual-modulation, e.g. phase and amplitude-modulation. In that embodiment, the back face 302 of the plate 300 is made partially transmissive (R2<1) and a 2D detector array 114' is placed behind the plate. In this way, no interference is detected, but only the intensity of the original reconstructed data pattern. With this information, it is possible to compensate for the amplitude variations in the two reconstructed phase-modulated patterns P1 and P2 by either amplifying or levelling the phase signals in the reflected beams to facilitate signal-processing.

Any reference sign in the following claims should not be construed as limiting the claim. It will be obvious that the use of the verb "to comprise" and its conjugations does not exclude the presence of any other elements besides those defined in any claim. The word “a” or “an” preceding an element does not exclude the presence of a plurality of such elements.

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CLAIMS

1 A method for reading-out data recorded in a holographic medium (106) as a phase-modulated pattern of data pixels, comprising the steps of reconstructing said phase-modulated pattern (P), duplicating said reconstructed phase-modulated pattern in a first reconstructed phase-modulated pattern (P1) and a second phase-modulated pattern (P2) shifted from said first reconstructed phase-modulated pattern by an integer number of data pixels, and having interfere said first and second reconstructed phase-modulated patterns.

2 A method as claimed in claim 1, wherein said first (P1) and second (P2) reconstructed phase-modulated patterns are obtained by reflection of said reconstructed phase-modulated pattern (P) on each face (301, 302) of a plane parallel plate (300).

3 A method as claimed in claim 2, wherein the reflection and transmission coefficients of the faces (301, 302) of said plane parallel plate are determined so that the intensities of said first (P1) and second (P2) reconstructed phase-modulated patterns are substantially equal.

4 A method as claimed in claim 2, wherein the optical path difference between said first (P1) and second (P2) reconstructed phase-modulated patterns is tuned so as to maximize the interference contrast.

5 A method as claimed in claim 1, wherein data are also recorded in said holographic medium (106) as an amplitude-modulated pattern of data pixels and an amplitude information is detected so as to compensate for amplitude variations in said reconstructed phase-modulated patterns (P1, P2).

6 A method as claimed in claim 5, wherein said amplitude information is detected from the reconstructed amplitude and phase-modulated pattern transmitted through said plane parallel plate (300).

7 A device for reading-out data recorded in a holographic medium (106) as a phase-modulated pattern of data pixels, having means for duplicating a reconstructed phase-modulated pattern (P) in a first reconstructed phase-modulated pattern (P1) and a second phase-modulated pattern (P2) shifted from said first reconstructed phase-modulated pattern by an integer number of data pixels, and for having interfere said first and second reconstructed phase-modulated patterns.

8 A device as claimed in claim 7, wherein said duplicating means comprise a plane parallel plate (300) arranged in such a way that a beam (Bi, Bj) from a data pixel of said reconstructed phase-modulated pattern is duplicated in a beam (Bi1, Bj1) of said first

reconstructed phase-modulated pattern (P1) by reflection on one face (301) of said plane parallel plate and a beam (Bi2, Bj2) of said second reconstructed phase-modulated pattern (P2) by reflection on an other face (302) of said plane parallel plate.

9 A device as claimed in claim 8, wherein the angle of incidence (i) of said beams and the thickness (e) of said plane parallel plate (300) are determined so that a beam (Bj1) of said first reconstructed phase-modulated pattern (P1) and a beam (Bi2) of said second reconstructed phase-modulated pattern (P2) shifted by an integer number of data pixels are capable of interfering.

10 A device as claimed in claim 9, wherein the faces (301, 302) of said plane parallel plate (300) have reflection and transmission coefficients such that the intensities of interfering beams (Bj1, Bi2) are substantially equal.

11 A device as claimed in claim 9, wherein said plane parallel plate has means for tuning the optical path difference between interfering beams (Bj1, Bi2) so as to maximize the interference contrast.

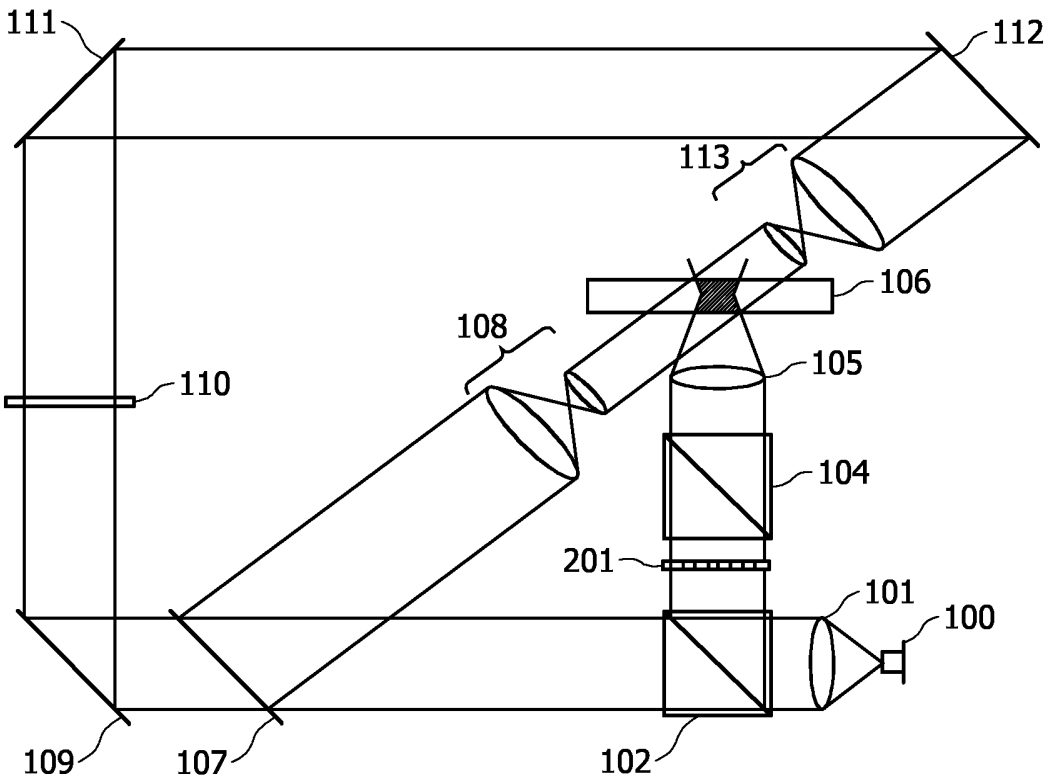


FIG. 1

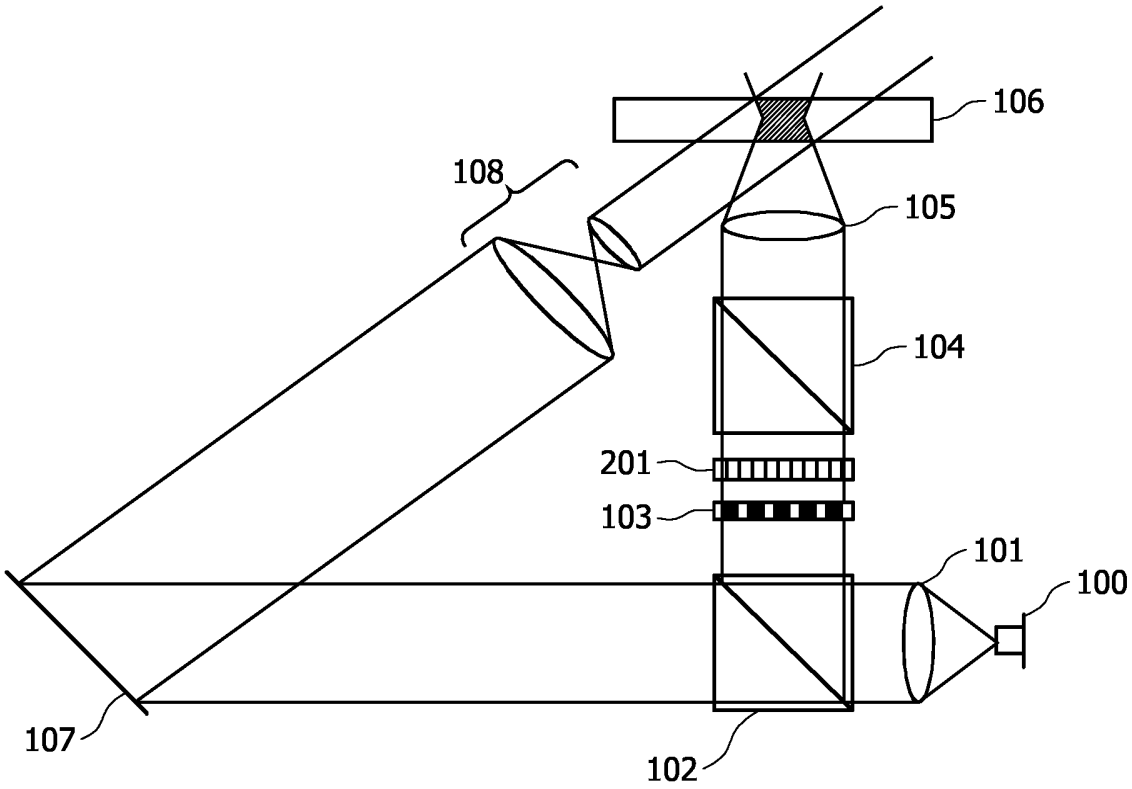


FIG. 2
(Prior Art)

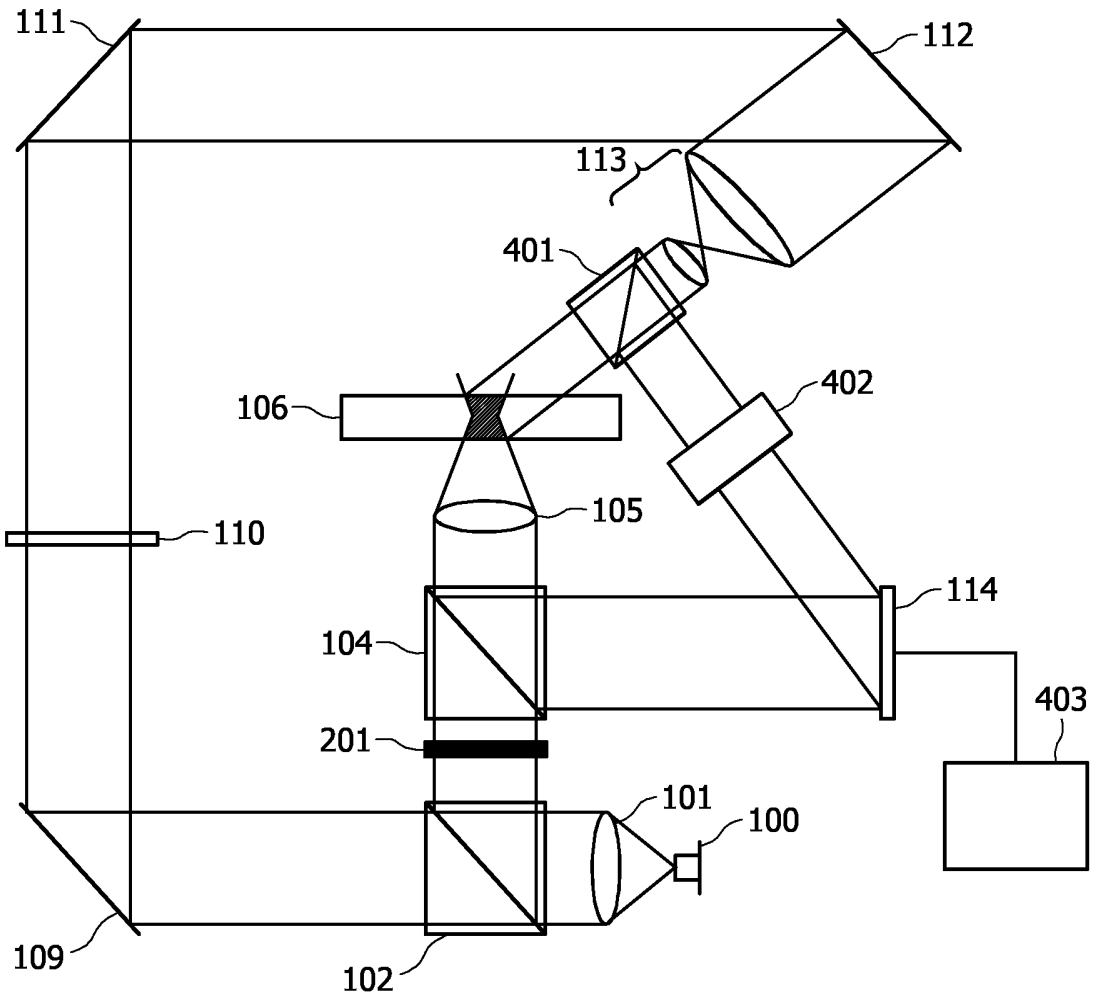


FIG. 3
(Prior Art)

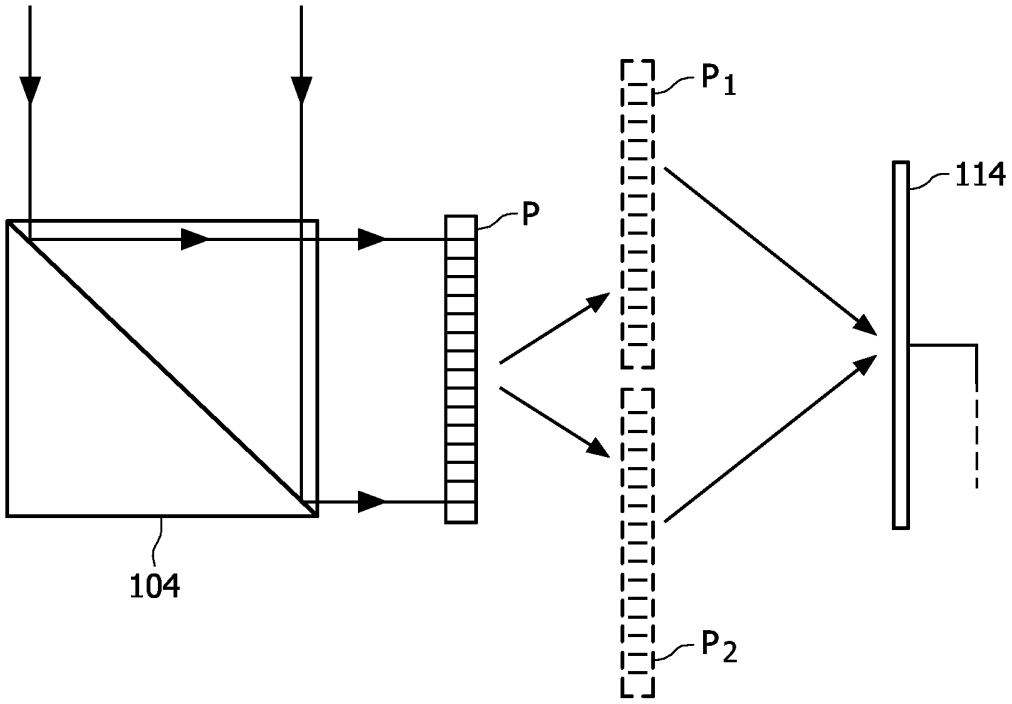


FIG. 4

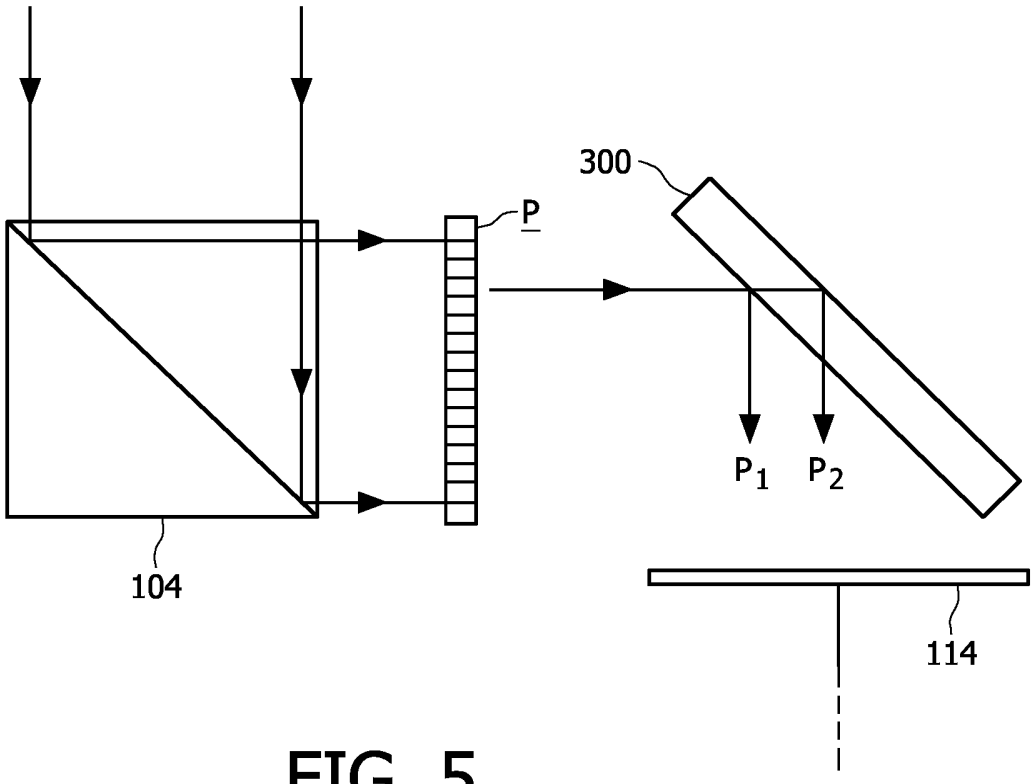


FIG. 5

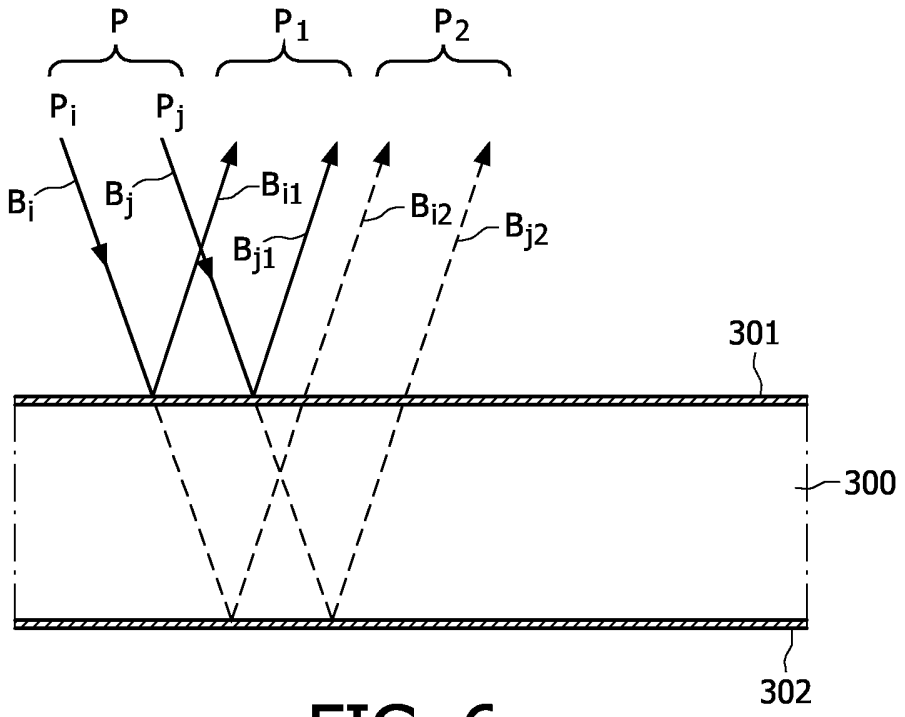

P
P1
P2
Pi
Pj
Bi
Bj
Bi1
Bj1
Bi2
Bj2
301
300
302

FIG. 6

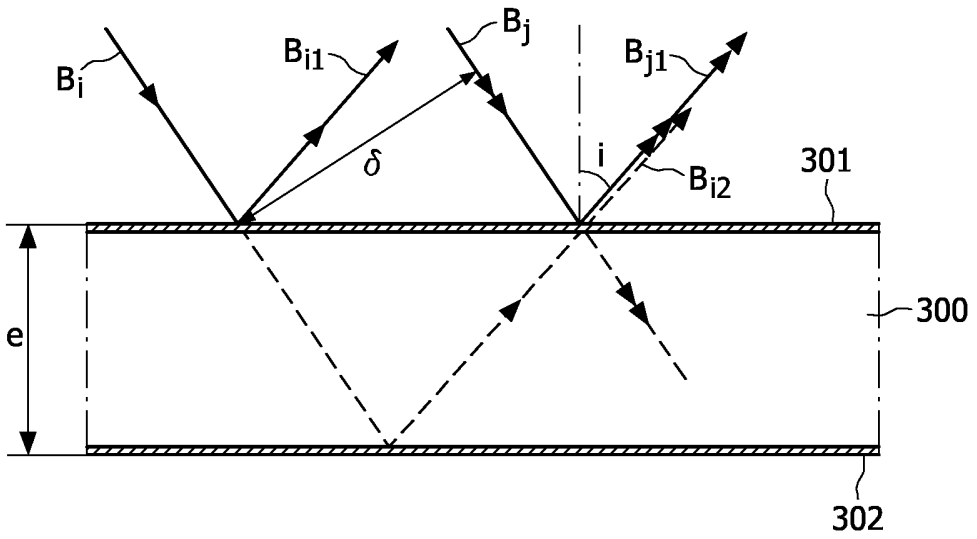

Bi
Bi1
Bj
Bj1
δ
i
Bi2
301
300
e
302

FIG. 7

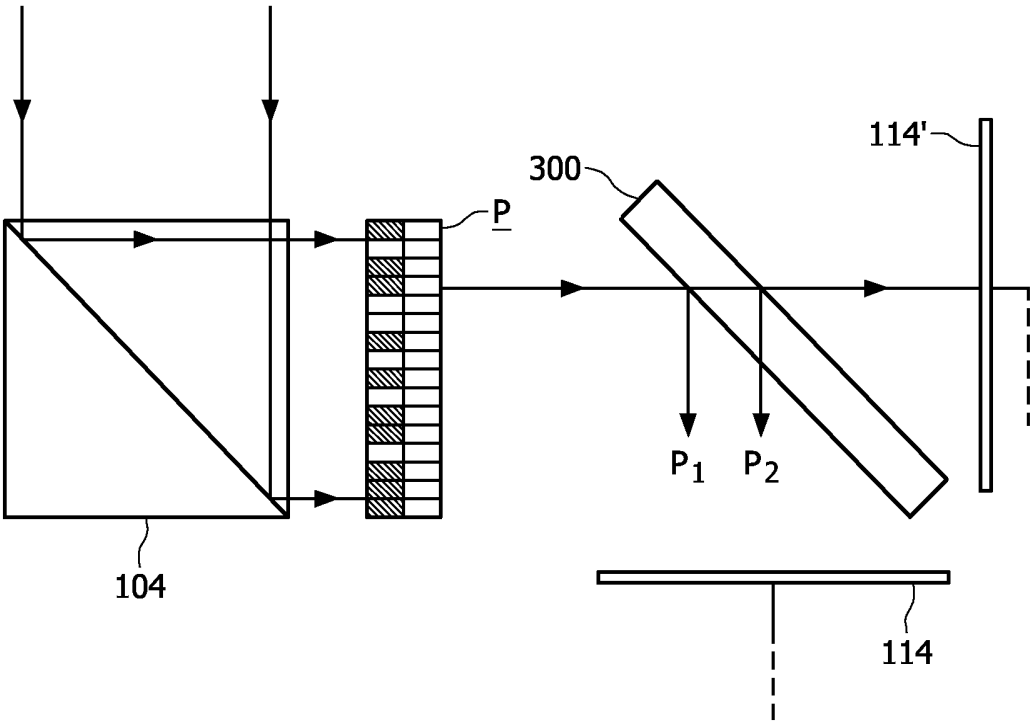


FIG. 8