

SPECIFICATION

Apparatus for the pointwise scanning of an information surface

The invention relates to apparatus for the pointwise scanning of an information surface, in particular to apparatus for reading a record carrier with an optically readable information structure, which apparatus comprises a radiation source, an illumination objective system for focussing the scanning beam emitted by the radiation source to a scanning spot on the information surface, and an observation objective system for concentrating radiation coming from the information surface on the plane of a radiation-sensitive detection system.

Such apparatus, intended for reading a round disc-shaped and radiation-reflecting record carrier on which a television programme is stored, is *inter alia* described in: "S.M.P.T.E. Journal" November 1976, Vol. 85, pages 881—886. The information structure comprises trackwise arranged areas which have a different optical property than the rest of the information surface. The information may be contained in the spatial frequency of the areas and, as the case may be, the lengths of the areas.

During reading the information structure is illuminated with a radiation spot which is larger than the areas, so that diffraction occurs. The information structure splits the scanning beam into a non-diffracted zero-order subbeam and a number of diffracted higher-orders subbeams.

If the record carrier is read in the reflection mode, as is shown in Figure 25 of the cited publication, the objective system which forms the scanning spot on the information structure also constitutes the objective system which concentrates the radiation which has been reflected by the information structure on a detector. The pupil of this objective system is symmetrically disposed relative to the zero-order subbeam. The maximum spatial frequency of the information structure which can still be read is dictated by the resolution of the objective system. When reading in the reflection mode using a focussed read beam, the maximum readable spatial frequency f_c , referred to hereinafter as the conventional cut-off frequency, is given by: $2 \cdot \text{N.A.} / \lambda$, in which N.A. represents the numerical aperture of the objective system and λ the wavelength of the read beam.

For reading a record carrier with a playing time of thirty minutes, which is rotated at 25 revolutions per second and in which the radial separation of the tracks is $1.7 \mu\text{m}$, the period of the information areas being of the order of $1 \mu\text{m}$, a helium-neon laser is used as radiation source, with $\lambda = 0.6328 \mu\text{m}$. An objective system with an N.A. = 0.4 should then be used. An objective system with such a comparatively large numerical aperture is rather expensive and, which is more important, has a comparatively small depth of focus of for example $4 \mu\text{m}$. In that case stringent requirements must be imposed on the servo

system which has been provided in the scanning apparatus for maintaining the scanning beam in focus on the information surface.

It has also been proposed to read a record carrier with the aid of a semiconductor diode laser, for example an AlGaAs diode laser, which emits radiation having a wavelength of the order of $0.88 \mu\text{m}$. If by means of such a diode laser the same resolution is to be obtained as with a helium-neon laser, an objective system with a larger numerical aperture, for example with N.A. = 0.55, will be needed and thus will have a smaller depth of focus.

In the last-mentioned case it would be attractive if the numerical aperture of the objective system could be reduced, whilst maintaining the resolution.

In other cases, where a comparatively large numerical aperture presents no serious problem, it would be attractive if the resolution could be increased, whilst maintaining the numerical aperture of the objective system.

Meeting these requirements is not only of importance when scanning coded information which is contained in an optical structure of a record carrier, but is generally of importance in those cases where optical information is scanned pointwise and is converted into an electrical signal, which is to be reproduced at a different instant or a different location. Examples of this are facsimile devices or devices by means of which optical representations or documents are converted into television signals.

Thus, it is desirable to provide scanning apparatus which complies with one of the said requirements or a combination of the two requirements. The invention provides apparatus for the pointwise scanning of an information surface, which apparatus comprises a radiation source, an illumination objective system for focussing the scanning beam emitted by the radiation source to a scanning spot on the information surface, and an observation objective system for concentrating radiation coming from the information surface of the plane of a radiation-sensitive detection system, wherein the observation objective system is disposed asymmetrically in the scanning direction relative to a zero-order subbeam of the radiation coming from the information surface, and wherein the detection system is constituted by a detector whose dimension in the scanning direction is small compared to the period of an interference pattern formed in the plane of the detector by the superposition of said zero order subbeam and a first order subbeam of the radiation coming from the information surface.

The method of information scanning employed in the apparatus in accordance with the invention differs from that employed in the apparatus as described in "S.M.P.T.E. Journal" vol. 85, pages 881—886 in two respects. In the last-mentioned apparatus the observation objective system is symmetrically illuminated by the zero-order subbeam, and the total radiation energy which

enters the objective system is detected. In the apparatus in accordance with the invention the observation objective system is asymmetrically illuminated by the zero-order subbeam and only a small portion of the radiation energy coming from the information surface and entering this objective system is detected.

In addition to the total zero-order subbeam, parts of the first-order subbeams enter the observation objective system is known apparatus. In the pupil of the objective system parts of the first-order subbeams overlap the zero-order subbeam. Use is made of the effect that the total radiation energy which passes through the objective system and which is detected by the detector varies during scanning. The variation results from the fact that the phases of the first order subbeams change relative to that of the zero-order subbeam. This variation can be detected as long as the first-order subbeams interfere with the zero-order subbeam within the pupil of the observation objective system. If the spatial frequency of the information structure is so high that the first-order subbeams fall just outside the pupil, so that interference does not occur in the pupil, the total radiation energy which is incident at the detector will no longer vary during scanning and the information can no longer be read. Thus, the conventional cut-off spatial frequency is then reached.

The invention is based on the recognition that in addition to the above mentioned effect a second effect occurs, namely that the interference pattern of a first-order subbeam and the zero-order subbeam "travels" during scanning, i.e. that the intensity distribution in the plane of the detector varies in time. This variation can be detected with a narrow detector, whose width is of the order of half a period of the interference pattern. A first-order subbeam and the zero-order subbeam then need no longer overlap in the pupil of the observation objective system, but these subbeams may pass through different parts of said pupil so as to be combined in the plane of the detector where, owing to the coherence of the scanning beam, an interference pattern is produced. It is then possible to shift the observation objective system in the direction in which one of the first-order subbeams is diffracted, so that at spatial frequencies higher than the conventional cut-off frequency this subbeam still falls partly within the pupil of the observation objective system and can be made to interfere with the zero-order subbeam. If the information structure is a radiation transmitting structure a separate illumination objective system and a separate observation objective system are employed.

Preferably, the information structure of a record carrier is a radiation-reflecting structure. In the case of a suitably oblique incidence of the scanning beam on the information structure, it is then also possible to employ a separate illumination objective system and a separate observation objective system. Then either the resolution can be increased substantially, whilst

maintaining the numerical aperture of the illumination objective system or the numerical aperture of the last-mentioned system can be reduced substantially, whilst maintaining the resolution.

However in a preferred embodiment of apparatus in accordance with the invention the illumination objective system and the observation objective system are constituted by one objective system whose optical axis makes an acute angle with the normal to the information plane.

The advantage of this apparatus is that it is simple and that the reflected scanning beam largely traverses the same optical elements as the scanning beam emitted by the radiation source, so that vibrations of the optical elements in the radiation path have virtually no effect on the resulting signal.

In order to increase the signal-to-noise ratio of the resulting signal the apparatus in accordance with the invention may have further detectors arranged on both sides of the detector in the scanning direction. The further detectors are each offset relative to the central detector and relative to each other by a distance equal to approximately half the period of the interference pattern.

Embodiments of the invention will now be described, by way of example, for reading a round disc-shaped record carrier, with reference to the accompanying drawings in which:

Figure 1 shows a previously proposed apparatus for reading a record carrier with a radiation-reflecting information structure,

Figure 2 illustrates the disposition of the subbeams of different orders relative to the pupil of the observation objective system in the apparatus of Figure 1,

Figure 3 illustrates the disposition of the subbeams of different orders relative to the pupil of the observation objective system in apparatus embodying the invention,

Figure 4 illustrates the principle of the invention,

Figure 5 shows apparatus in accordance with the invention for reading a radiation-transmitting information structure, and

Figures 6 and 7 show a first and a second embodiment of apparatus in accordance with the invention for reading a radiation-reflecting information structure.

Figure 1 shows a round disc-shaped record carrier 1 in radial cross-section. The tracks 2 of the reflecting information surface 3, which tracks comprise information areas, not shown, extend perpendicularly to the plane of drawing. The information structure may be an amplitude structure, the information areas having a different coefficient of reflection than the rest of the surface 3. However, the information structure may alternatively be a phase structure, as is shown in Figure 1, the information areas being constituted by pits in the surface 3.

During scanning the record carrier is rotated with the aid of a spindle 4 which is driven by a rotary motor 5. A radiation source 6, for example

helium-neon laser or a semiconductor diode laser, produces a scanning beam *b*. A mirror 8 reflects this beam to an objective system 9, which is schematically represented by a single lens. In the path of the beam *b* an auxiliary lens 7 is included, which ensures that the pupil of the objective system is filled in an optimum manner. Then a scanning spot *V* of minimum size is formed on the information structure.

The scanning beam is reflected by the information structure and, as the record carrier rotates, is modulated in accordance with the sequence of the information areas in a track being read. By moving the scanning spot and the record carrier radially relative to each other by means known *per se* and not shown, the entire information surface 3 can be scanned.

The modulated scanning beam again traverses the objective system 9 and is reflected by the mirror 8. The radiation path includes means for separating the modulated and the unmodulated scanning beam. These means may for example comprise a polarization-sensitive splitter prism and a $\lambda/4$ plate. For the sake of simplicity it has been assumed that in Figure 1 the said means consist of a semitransparent mirror 10. This mirror reflects the modulated scanning beam to a radiation-sensitive information detector 11. The output signal S_1 of this detector is modulated in accordance with the information being scanned and can be applied to a demodulator 12 in which the signal is processed and rendered suitable for reproduction with, for example, a television set 13.

The part of the information surface in the vicinity of the scanning spot *V* behaves as a two dimensional diffraction grating, which splits the incident scanning beam into an undiffracted zero-order subbeam and diffracted first-order subbeams and higher-order subbeams. The zero-order subbeam and parts of the diffracted subbeams again enter the objective system 9. In the plane of the exit pupil of the objective system the centres of the various subbeams are spaced from each other. Figure 2 shows the situation in this plane.

The circle 15 with the centre 18 represents the cross-section of the zero-order subbeam in this plane. The circles 16 and 17 with the centres 19 and 20 represent the cross-sections of the tangentially diffracted (+1,0) and (-1,0) order subbeams. The X-axis and the Y-axis in Figure 2 correspond respectively to the tangential direction, or the scanning or track direction, and the radial direction, or the direction transverse to the scanning direction, in the information plane 3. Since only tangentially diffracted subbeams are of interest for the present invention, the radially diffracted subbeams will not be considered.

In Figure 2 the dashed circle 21 represents the pupil of the objective system 9. For the situation shown in Figure 1 the zero-order subbeam fills the pupil entirely, so that in reality the circles 15 and 21 coincide. Only that part of the radiation coming from the record carrier which falls within the pupil is used for information scanning. For the purpose

of scanning use is made of the phase variations in the (+1,0) and (-1,0) order subbeams relative to the zero-order subbeam.

In the hatched areas in Figure 2 said first-order subbeams overlap the zero-order subbeam and interference occurs. The phases of the first-order subbeams vary if the scanning spot moves relative to an information track. As a result of this the intensity of the total radiation passing through the exit pupil of the objective system varies.

When the centre of the scanning spot coincides with the centre of an information area (— or pit) a certain phase difference ϕ exists between a first-order subbeam and the zero-order subbeam.

When the scanning spot moves from a first area to a second area, the phase of (+1,0) order subbeam increases by 2π . Therefore, as the scanning spot moves in the tangential direction the phase of said subbeam relative to the zero-order subbeam varies with ωt where ω represents a time frequency which is determined by the spatial frequency of the information areas and by the speed with which the scanning spot moves over a track. The phase ϕ (+1,0) of the (+1,0)-order subbeam relative to the zero-order subbeam may then be represented by:

$$\phi (+1,0) = \phi + \omega t.$$

The intensity variation caused by interference of the (+1,0)-order subbeam with the zero-order subbeam could be detected by a radiation-sensitive detector 23, represented by dashed lines in Figure 2, which detector is disposed in the plane of the exit pupil or in an image thereof. For a specific phase depth of the information structure, for which $\phi = \pi$ rad., the intensity variation over the exit pupil is symmetrical. Then, as shown in Figure 1, the beam parts traversing the two areas of overlap can be concentrated on one detector. The time dependent output signal of the detector 11 may then be represented by:

$$S_1 = A(\phi) \cdot \cos \phi \cdot \cos \omega t,$$

where $A(\phi)$ decreases with decreasing value of ϕ . For a specific phase depth of the information structure the amplitude $A(\phi) \cdot \cos \phi$ is constant.

The frequency of the signal S_1 is then given by the information which is instantaneously scanned.

So far only the first-order subbeams have been discussed. It is obvious that the information structure will also diffract radiation to higher-orders. The radiation energy in the higher diffraction order is low and the diffraction angles are so large at the high spatial frequencies of the information structure considered here, that only a small part of the higher order beams falls within the pupil of the objective system 9. Therefore, the influence of the higher-order subbeams may be neglected.

The optical scanning system outlined in the foregoing has a certain cut-off frequency f_c . The distance *d* between the centre 22 of the pupil of the objective system 9 and the centres 19 and 20

of the first-order subbeams is determined by: $\lambda.f$, where f represents the spatial frequency of the information areas in the scanning direction. Figure 2 represents the situation in which the frequency f is slightly higher than half the cut-off frequency f_c . If the frequency f increases, the $(+1,0)$ order subbeam moves to the right and the $(-1,0)$ order subbeam moves to the left, and the distance d increases. For a given value of f , referred to as the conventional cut-off frequency f_c , the circles 16 and 17 no longer intersect the circle 21, but are merely tangent to this circle. The first-order subbeams then no longer pass through the pupil of the objective system 9, and these beams can no longer be made to interfere with the zero-order subbeam in the pupil. The information of the record carrier can then no longer be scanned by detecting the total radiation energy which passes through the pupil of the objective system.

For the situation illustrated in Figure 1 where only one objective system is provided which serves as illumination objective and as observation objective, the conventional cut-off frequency is given by:

$$f_c = 2 \text{ N.A.} / \lambda$$

If, as is the case if scanning a radiation-transmitting record carrier, a separate illumination objective and a separate observation objective are provided the cut-off frequency is given by:

$$f_c = (\text{N.A.}_v + \text{N.A.}_w) / \lambda$$

where N.A._v and N.A._w respectively represent the numerical aperture of the illumination objective system and of the observation objective system.

In accordance with the invention the observation objective system is disposed so that the centre 22 of the pupil of this objective system no longer coincides with the centre 18 of the zero-order subbeam, but is shifted in the direction of the centre 19 or 20 of one of the first-order subbeams. Thus at spatial frequencies which are higher than the aforementioned conventional cut-off frequency f_c a part of a first-order subbeam still passes through the pupil of the observation objective system.

Figure 3 represents the situation in which the pupil 21 has been shifted to the right relative to the situation in Figure 2. The distance d between the centre 18 of the zero-order subbeam and the centres 19 and 20 of the first-order subbeams, and thus the spatial frequency of the information areas is substantially greater than in the case of Figure 2, approximately by a factor 3. This spatial frequency is approximately 1.5 times the cut-off frequency of the system in accordance with the Figures 1 and 2. Nevertheless, a substantial portion of the $(+1,0)$ order subbeam falls within the pupil of the observation objective system. Now only a part of the zero-order subbeam enters said pupil, whilst the $(-1,0)$ order subbeam falls

entirely outside in the pupil.

As is shown in Figure 4, the parts of the zero-order subbeam $b(0,0)$ and of the first-order subbeam $b(+1,0)$ which fall within the pupil of the observation objective system 25 are concentrated on the detection plane 26. Since the scanning beam is a coherent beam, the radiation parts will interfere with each other in the plane 26, so that an intensity pattern I is produced which varies in the X direction as is represented by the curves 27, 28 and 29 in Figure 4. The uninterrupted curve 27 represents the intensity variation in the case that the scanning spot is situated exactly above the centre of an information area. If the scanning spot moves away from this centre along a track to a subsequent information area, the intensity pattern for two consecutive instants will have a variation in accordance with the dash-dot curve 28 and the dashed curve 29 respectively. During scanning the intensity pattern thus "travels" over the detection plane. For a narrow detector having a fixed location, such as the detector 30 in Figure 4, the radiation intensity which is received consequently varies during scanning. Thus, the output signal of this detector varies depending on the information being read instantaneously.

The width of the detector 30 should be small relative to the period of the intensity pattern. The period of the intensity pattern is determined by the local spatial period of the information details in the information surface to be scanned. For a specific information structure in a record carrier to be scanned or for other documents or optical representations to be scanned the spatial frequencies are known. The width of the detector 30 can then be adapted accordingly.

The signal from the detector 30 may be applied directly to a demodulator 12, in a similar way as in Figure 1. The signal/noise ratio of the read-out signal can be improved by arranging two detectors 31 and 32 on both sides of the detector 30 and at a distance of approximately half the period of the intensity pattern. The output signals of these detectors may then be combined and subtracted from the signal from the detector 30 in a differential amplifier 33. The output of this amplifier, in its turn, is connected to the input of a demodulator 12.

In the apparatus in accordance with the invention the observation objective system is illuminated obliquely, or asymmetrically, by the zero-order subbeam. A parameter s may be introduced which is a measure of the offset, measured in the plane of the pupil of the observation objective system, of the centre 22 of this pupil relative to the centre 18 of the zero-order subbeam. The parameter s may be defined as this offset e normalized with half the pupil diameter a , see Figure 3. For a symmetrical illumination of the pupil, as in Figure 2, $s = 0$. For the situations shown in Figures 3 and 4 $s = 1.5$.

The cut-off frequency f_c of a scanning apparatus with oblique illumination of the observation objective system is given by:

$$f'_c = \frac{N.A._v + N.A._w}{\lambda} \left(1 + \frac{s}{2}\right) \text{ for } s < 2.$$

For $s = 1.5$ and $N.A._v = N.A._w$, $f'_c = 3.5 N.A./\lambda$, i.e. 1.75 times the conventional cut-off frequency of the apparatus in accordance with Figures 1 and 2.

- 5 For $s = 2$ no radiation of the zero-order subbeam traverses the pupil of the observation objective system, so that no interference can occur between the zero-order subbeam and the (+1,0)-order subbeam. If s is approximately 2, the
10 a.c. signal produced by the detector 30 is very small. In practice an s value of approximately 1.5 is therefore selected.

- Figure 5 schematically illustrates how the invention can be realized in an apparatus for
15 reading a radiation-transmitting record carrier. In this Figure the record carrier is represented by the information surface 3. The scanning beam from a radiation source 34 is focussed on this surface to a scanning spot V by the illumination objective
20 system 35. Behind the information surface 3 an observation objective system 25 is disposed, whose optical axis makes an acute angle with that of the illumination objective system 35. In this Figure and in Figures 6 and 7 the optical axes are represented by dash-dot lines. The observation
25 objective system intercepts part of the radiation of the subbeam $b(0,0)$ and of the subbeam $b(-1,0)$ and concentrates these radiation components on the plane of the detector 30, in which plane
30 interference occurs.

- Figure 6 shows a part of an apparatus in accordance with the invention for scanning a radiation-reflecting information surface. In view of the foregoing this Figure is self-evident. The
35 radiation components of the scanning beam reflected by the information surface, which components are made to interfere, are now spatially separated from the radiation emitted by the radiation source. In contradistinction to the
40 apparatus in accordance with Figure 1 no additional beam splitting means need be used.

- In the apparatus in accordance with Figures 5 and 6 the observation objective system may have a different numerical aperture than the illumination
45 objective system. The first-mentioned objective system now need only concentrate part of the radiation coming from the information surface on the plane of the detector 30. The depth of focus of this objective system may be smaller than that of
50 the illumination objective system with which a small scanning spot is formed on the information surface. By selecting a numerical aperture for the observation objective system greater than that of the illumination objective system, the resolution of
55 the optical scanning system can be increased whilst maintaining the numerical aperture of the illumination objective system and maintaining the s -value.

- Figure 7 shows a part of an apparatus for
60 scanning a radiation-reflecting information surface which employs only one objective system. In this apparatus the illumination objective system itself

concentrates a part of the subbeam $b(0,0)$ and of the subbeam $b(-1,0)$ on the plane of the detector.
65 In a similar way as in the apparatus in accordance with Figure 1 the parts of the subbeams $b(0,0)$ and $b(-1,0)$ passing through the objective system 9 can be separated from the beam emitted by the radiation source by means of for example a
70 semitransparent mirror.

- The arrangement of Figure 7 is particularly suitable for use with a diode laser 36 as radiation source. Use can then be made of the so-called feedback effect, which effect has been described
75 *inter alia* in United States Patent Specification 3,941,945. This feedback effect means that radiation which is reflected to the diode laser by the information surface may give rise to a further radiation emission by the diode laser under certain
80 circumstances. The radiation emitted by the diode laser is then dependent on the intensity of the radiation reflected to the diode laser and thus on the information being scanned instantaneously. The variation in the radiation emitted by the diode
85 laser can be detected with a detector 37 which is disposed behind the diode laser. The variation in the diode laser caused by the information being scanned can also be detected by measuring the variation in electrical resistance of the diode laser.
90 The diode laser itself is then used as information detector. As the aperture through which the diode laser emits its radiation is small, this diode laser constitutes a suitable detector for a scanning apparatus in accordance with the invention. As
95 furthermore the forward path of the scanning beam is the same as the return path, the diode laser is automatically well-aligned and any vibrations of optical elements in the radiation path will not affect the detector signal.

- 100 Since a scanning apparatus in accordance with the invention makes use of the interference between the zero-order subbeam and one first-order subbeam, this apparatus is suitable for reading deep and shallow phase structures and
105 amplitude structures.

- A record carrier with an optical information structure in which for example a television programme is stored, is preferably provided with a so-called protective layer. This is a radiation-
110 transmitting layer of a certain thickness, which ensures that dust particles, scratches and the like remain at a suitable distance from the optical information structure. These dust particles and the like then cannot not seriously affect the read beam
115 which has been focussed on the information structure. In the situation shown in Figure 5 in which the illumination beam is perpendicularly incident on the record carrier, such an additional protective layer presents no additional problems.
120 In the case of an oblique incidence of the illumination beam on the record carrier, as is the case in Figures 6 and 7, the protective layer may give rise to additional aberrations such as coma and astigmatism in the scanning spot. The illumination objective system can be corrected in
125 respect of these aberrations. However, such a correction is only valid for one specific oblique

position of the objective system relative to the record carrier. Care must then be taken that said oblique position is strictly maintained.

- In the foregoing the invention has been described on the basis of an optical scanning apparatus. It will be evident that because of the analogy between scanning with a light beam and with an electron beam, the invention may also be utilized in an electron microscope. In such a microscope the resolution can then for example be increased, without adapting the lenses.

CLAIMS

1. Apparatus for the pointwise scanning of an information surface, which apparatus comprises a radiation source, an illumination objective system for focussing the scanning beam emitter by the radiation source to a scanning spot on the information surface, and an observation objective system for concentrating radiation coming from the information surface on the plane of a radiation-sensitive detection system, wherein the observation objective system is disposed asymmetrically in the scanning direction relative to a zero-order subbeam of the radiation coming from the information surface, and wherein the detection system is constituted by a detector

whose dimension in the scanning direction is small compared to the period of an interference pattern formed in the plane of the detector by the superposition of said zero order subbeam and a first order subbeam of the radiation coming from the information surface.

2. Apparatus as claimed in Claim 1, wherein the illumination objective system and the observation objective system are constituted by one objective system whose optical axis makes an acute angle with the normal to the information plane in the scanning direction.

3. Apparatus as claimed in Claim 1 or 2, wherein further detectors are arranged on both sides of the detector in the scanning direction.

4. Apparatus as claimed in Claim 3, wherein said further detectors are spaced at half the period of said interference pattern from the detector, and wherein means are provided for deriving an information signal from the difference between the sum of the output signals of said further detectors and the output signal of the detector.

5. Apparatus for the pointwise scanning of an information surface substantially as described with reference to Figures 4, 5, 6 or 7 of the accompanying drawings.



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