The invention relates to a novel system for the recording of data by the storage of digital information in optical form.

In technologies for the digital optical storage of information, the maximum possible storage density is limited by diffraction at the wavelength of the writing or reading operations. For the optical wavelengths commercially available in the form of laser diodes, this limit on density can be placed, for example, in the vicinity of one bit per square micrometre. Below this, the laser light is diffracted by the molecular structure of the material in which the recording is etched, and it is no longer possible to distinguish adjacent elementary dots.

To increase the density of digital information that can be stored in a disk, i.e. to increase the quantity of information stored without increasing the surface area of the disk or to reduce the surface area of the disk without reducing the quantity of information, the use of a stack of photosensitive layers reacting to different wavelengths (like superimposed photographic layers) has already been proposed: information items are stored in each layer and each of them can be read only by a specific laser having a well-determined wavelength that differs from the wavelengths used to read the information stored in the other layers. The absorption peaks of the different layers should be at wavelengths that are clearly separated from one another to enable discrimination among the items of information. The upper layers have to be transparent to the wavelengths of sensitivity of the lower layers. The difficulty therefore lies in finding, for the different layers, materials that have the requisite properties in terms of spectral selectivity, sensitivity (for the writing), transparency and information-retention time.

US Patent 3987421 has also proposed storing several information items in the same zone using surface diffraction gratings, several gratings diffracting at different frequencies being mixed at the surface of the

same zone.

The invention proposes an original approach, as defined in the independent Claims 1, 14 and 15, by which the quantity of digital information available per unit of surface area is greatly increased. This approach makes use of a principle which differs from the superimposition of layers.

This approach uses a layer of transparent material, in the thickness of which diffraction optical gratings may be formed. Several different diffraction gratings are mixed in each elementary zone of the layer, the digital information being defined by the presence or absence, in a determined elementary zone, of a grating that diffracts at a determined wavelength, each grating being capable of selectively diffracting an electromagnetic radiation of determined wavelength while diffracting scarcely or not at all radiations at wavelengths which are strongly diffracted by the other gratings. Elementary zone is intended to mean a zone of lateral dimensions which are just sufficient to store a bit of digital information in the form of a diffraction grating having fringes parallel to the surface. It should therefore be understood that the invention proposes to store in this elementary zone with dimensions normally adapted to the storage of one bit of information, several bits each represented by the presence or absence in this zone of a grating diffracting at a respective wavelength. The gratings are intimately mixed and are located in the thickness of the layer, the fringes being essentially parallel to the surface.

The layer is preferably a layer of transparent material with photo-induced variation in refractive index; several bits of information are written in one and the same elementary zone of the layer, in the form of the presence or absence of diffraction gratings with different spacings, each bit corresponding to a grating with a determined spacing that is different from the spacing of the other bits.

In standard optical recording systems, different

information bits have to be stored in different elementary geographical regions; the invention proposes an original system wherein several different bits may be registered at the same location. The information corresponding to the different bits is represented by the spacings of the diffraction gratings superimposed on (mixed with) one another in the same elementary region.

Moreover, since the diffraction gratings are recorded "vertically", i.e. with fringes parallel to the layer surface, the lateral dimensions of each elementary information zone are minimized, so that the density of digital information stored can be considerably increased.

It can be seen that, if several different gratings can be superimposed in the same zone, and if the spacing of each of the superimposed gratings present in this zone can be ascertained, then the storage density is increased as compared with all the standard systems in which only one bit can be stored in an elementary region.

Now, a diffraction grating with a constant spacing very selectively diffracts only certain light wavelengths that go through it. It is therefore possible, by using beams of appropriate wavelengths, to detect the presence or absence of diffraction gratings with determined spacings, even if several gratings are superimposed at the same point, provided that the wavelengths diffracted by each grating are quite different from the wavelengths diffracted by the other gratings.

The recording medium used is therefore a layer of material with photo-induced index variation, i.e. a material with a refractive index that will vary locally and permanently under the effect of a photon energy applied locally to the material. And the energy will be applied in such a way that permanent index modifications are recorded according to a diffraction grating pattern, as fringes parallel to the surface of the layer, in the thickness of this layer.

A grating will be registered preferably by using a laser focused on a small elementary region of this

layer, perpendicularly to the layer thickness. It is simplest to combine the laser beam with its own reflection in a mirror so as to produce interferences in the zone in which the beams are combined (the zone which, by arrangement, will be placed in the thickness of the recording layer); the combining of the beams produces an interference grating with a geometric spacing that is directly related to the wavelength of the laser (the spacing is the wavelength divided by twice the refractive index of the material). The light energy available in the combined beams is chosen so as to be high enough for the interference grating to prompt a local modification of the refractive index of the layer according to the distribution of light energy, i.e. according to the pattern of the interference grating. There is therefore permanent recording, in the layer, of an optical grating with a well-determined spacing related to the wavelength of the laser, in the manner of a hologram, but in the thickness of the layer.

If the operation is repeated with a laser having a different wavelength, another interference grating with a different spacing can be registered at the same place. Several gratings can thus be superimposed at the same place; what distinguishes them is their respective spacing in the direction of the thickness, whereas they cannot be distinguished by their location in the plane of the layer since they occupy the same region of layer.

To read the information, it must therefore be possible to determine whether there is a grating with a determined spacing in a determined elementary zone. To this end, the invention uses reading lasers with the same frequency as the writing lasers (one tunable laser or several lasers). Passage of the reading laser through a diffraction grating that has been registered in the layer of material by a writing laser of determined wavelength prompts, if the reading beam has the same wavelength as the writing beam, a general diffraction of the beam and, in particular, prompts a partial rearward diffraction. On the contrary, when the reading laser has a wavelength

different from that used to register engraving of the grating, it goes through the grating without being diffracted. It is thus possible to detect the existence or non-existence of this diffraction, hence the presence or absence of a grating with a determined pitch. The selectivity is high, all the more so the greater the number of spatial periods of the diffraction grating.

The disk according to the invention, storing the digital information in optical form, therefore includes a layer of material with photo-induced variation of refractive index, and several diffraction gratings mixed, in the thickness of the layer, in each elementary information storage zone.

The reading method according to the invention is generally expressed by the fact:

- that a reading laser is selected having a frequency determined among several possible frequencies,
- and that in each elementary zone of a surface layer of the disk, the presence is detected of a physical pattern that is diffractive for this frequency and non-diffractive for the other frequencies. The diffracting patterns are constituted by periodic spatial variations of the optical index, within each elementary zone, in the direction of the thickness of the layer, i.e. essentially perpendicularly to the surface.

The method may consist:

- either in choosing a reading laser with a well-determined wavelength and in reading the successive adjacent regions solely in order to detect therein the gratings having a spacing corresponding to the laser chosen, and then changing, if necessary, the reading wavelength,
- or in reading each zone with several successive reading wavelengths before passing on to the next zone.

If necessary, in particular instances, it is possible to envisage the disk having two or more layers of material with photo-induced index variation, which layers would be sensitive, in writing mode, to very different ranges of wavelengths and would each be transparent to the wavelengths of sensitivity of the other layers. Superimposed gratings will then be present in each layer. It would thus be possible to further increase the density of information superimposed in one and the same surface region of the disk. It is possible, for example, to imagine superimposing an image information item and a sound information item on one and the same optical disk, the sound information item being set up in a lower layer that can be read with a laser having a greater wavelength, hence a lower resolution, than the image information item. These two information items can then be read simultaneously or almost simultaneously. Several reading "tracks" are superimposed for each layer, which are distinguished from one another not by their physical location but by the laser wavelengths that enable them to be read.

Other features and advantages of the invention shall appear from reading the following detailed description, made with reference to the appended drawings, wherein:

- Figure 1 shows the general principle of optical recording according to the invention;
- Figure 2 shows a schematic diagram of the reading of recorded information;
- Figure 3 shows the general shape of the diffraction selectivity curves.

Figure 1 shows the general principle of the invention: a laser beam 10 with a wavelength L is focused by lenses 12 on a very small surface zone 14 of a layer of a material having a refractive index N that can be locally modified by the photon energy dissipated locally in the layer.

For reasons of convenience of representation, the

drawing is not done to real scale. For example, the thickness of the layer may be some tens of micrometres at least, or even 100 to 200 micrometres; the surface area of the zone 14, i.e. that of the focusing spot of the laser beam, may be of the order of one square micrometre; and the wavelength L of the order of one micrometre or less (visible wavelength). The distance between the focusing means 12 and the surface of the layer is a few millimetres.

The laser beam therefore goes through the layer along a sort of cylindrical tube having a height that is the thickness of the layer and having a cross-section, of the order of one square micrometre, that represents an elementary surface disk zone wherein several binary information items are to be registered.

The layer is preferably plane (it is deposited on a plane support disk) so that the surface can easily be scanned by being made to rotate under the laser beam.

The following procedure is used for writing information items onto the disk: the layer is formed on a reflecting surface 18 (reflecting for the wavelength L of the laser). For instance, provision may be made for the layer to have been initially deposited on a transparent disk and for this substrate to be flipped over to place the layer in contact with the reflecting surface of a support which is not integral with the disk; this allows easier separation of the disk from the reflecting layer if necessary. However provision also could be made for the layer to be formed directly on the reflecting support and for it to be separated from this support subsequently (by known means) if so desired.

The laser beam goes through the layer and is combined with its own reflection in the mirror 18. This results in interferences having the same scale as the wavelength within the actual thickness of the layer, these interferences corresponding to maxima and minima of light energy, as is well known in the wave theory of light.

The layer 16 reacts with the energy provided by

the laser beam, locally modifying its refractive index, all the more so the greater the energy provided. The refractive index is therefore modified in a pattern corresponding to that of the interference grating: there are maxima and minima of index variations according to the same pattern as the maxima and minima of the interference grating. These index variations are permanent. They are symbolized in Figure 1 by a net of lines with modified index N+dN but, in practice, the grating is more complex than a simple net of juxtaposed lines.

The recording is a sort of hologram in the thickness of the layer 16.

Suitable materials for the layer 16 are precisely materials for holograms. Appropriate photopolymers are described by Booth in Applied Optics, Vol. 14, p. 593, 1975, or by Monroe, Smothers, Krebs, Mickish in SPIE Symposium On Hybrid Imaging Systems, Rochester, New York, 1988. Materials such as lithium niobate, $LiNbO_3$, bismuth germanate, $Bi_{12}GeO_{20}$ or bismuth silicate $Bi_{12}SiO_{20}$ may also be suitable.

The order of magnitude of the index variation is not high; its maximum value is, for example, one per cent (1%); but this is far more than is needed for the reading operation, as shall be seen further below, provided that the thickness of the layer is sufficient to permit the housing therein of a large number of spatial periods of the interference grating.

Actually, a far lower value of laser beam energy is applied than that needed to produce this 1% variation in index: rather, an overall energy is applied such that the maxima of the interference gratings prompt local index variations of the order of 0.02%.

In this way, the layer is not saturated with a single recording of an interference grating. On the contrary, a wide margin remains for the recording, at the same place, of other gratings by means of lasers with different wavelengths. With maximum index variations of 0.02% for each grating, several tens of different

gratings, or even a hundred or so of them, can be recorded in one and the same elementary region 14 without saturating the layer.

In short, if the maximum possible variation of the index is X% of the initial index, and if it is desired to be able to superimpose K gratings at one and the same place, then each of the gratings should individually correspond roughly to an index variation of X/K %.

The information writing operation shown in Figure 1 is therefore repeated with different laser wavelengths at each point of the surface of the layer 16. Further below, we shall see how the wavelengths are chosen: the problem is one of discrimination during the reading operation.

By way of indication, the energy used for registering in the photopolymer may be 100 millijoules per cm^2 to obtain a 0.02% variation in index. This energy corresponds to 1 nanojoule for 1 square micrometre. The registration period for a point may be 100 nanoseconds, the laser power needed for the registration then being 10 milliwatts and, taking account of the overall efficiency of the optical system, this power may be produced by a 50-milliwatt or 100-milliwatt laser.

For the reading operation it is preferable (but not absolutely indispensable) that the layer 16 should lie no longer on a reflecting surface 18 but rather on a transparent or absorbent support. Anyway, reading will not necessarily be performed on the recorded layer 16 itself, but rather on a disk obtained by holographic duplication, this replica disk having no reason to include a reflecting layer.

The reading of a binary information item recorded at a given point consists in the focusing, at this point, of a laser beam of the same wavelength as that used to register the information item, but of lower energy. Either registration has been effected and a holographic type interferential grating is registered in the form of a pattern of variations in the optical index of the

material, or else no registration has been effected and there is no grating, or at least there is no grating corresponding to the same registration wavelength since there may be some corresponding to other wavelengths.

If there is a pattern, the laser beam is highly diffracted since the spacing of the pattern is that of the interferences created by the same wavelength. A part of the diffracted light is sent back (backscattered) and may be detected by a photodetector.

If there is no pattern (corresponding to this wavelength), the laser beam goes through the layer without diffraction and no light is backscattered. This is true even if there are patterns that have been registered at the same point and correspond to other wavelengths: the laser beam goes through these patterns without diffraction and no light is backscattered.

Figure 2 shows the principle of this laser reading operation. Naturally, the energy of the reading laser beam is far lower than that of the writing beam so as not to induce any index variation in the material during the reading operation.

The layer 16 is on a preferably transparent support 20 (the substrate of a disk). The reading laser beam 22 transmitted through a semi-reflecting slanting mirror 24 is focused by an optic 26 on a small zone 14 of the surface of the layer 16 and throughout the entire thickness of the layer beneath this surface. Light 28 is possibly backscattered by the presence of a diffraction grating 30 in the layer 16 if this grating has been registered at the same wavelength as that of the reading laser 22. This light is sent back through the optic 26 to the mirror 24. The mirror 24 sends it back to an optical system 32 which focuses it on a photodetector 34. The photodetector gives the required binary information on the presence or absence, at a given place, of a diffraction grating corresponding to the wavelength of the reading laser.

The laser is tunable so that the disk can be read with different wavelengths corresponding to the different

writing wavelengths. Or else, several different lasers are provided, and are used in turn.

The movement of the laser in relation to the surface of the disk, in reading as well as in writing mode, is of a standard type for optical recording media: the best is to use a plane disk to support the layer 16 and to make the disk rotate in relation to a fixed laser beam oriented perpendicularly to the surface of the disk. The position of the beam in relation to the disk is, for example, servo-linked in a standard way to a track etched in the disk.

Figure 3 shows the efficiency of diffraction of a laser beam by a diffraction grating created in the layer 16 by photo-induced index variation. This efficiency is the ratio between the intensity of the light diffracted backwards and that of the incident beam. Even if this efficiency is low (a small proportion of the incident beam returns backwards and can be collected at the photodetector), it is very selective as a function of the wavelength, and there is a very sharp peak for the wavelength corresponding precisely to the wavelength of the diffraction grating writing laser.

As can be seen in Figure 3, the efficiency of diffraction as a function of the wavelength is a curve of the type $(\sin x/x)^2$, i.e. it has a very marked maximum at the wavelength L and, on either side of this maximum, it exhibits alternate secondary minima and maxima that have far smaller amplitudes than the main peak.

The spectral selectivity may be expressed by the ratio d10/LO between the wavelength gap d10 at mid-height (corresponding to a 50% drop in efficiency) and the wavelength LO at the centre of the main peak.

The efficiency exhibits minima between the peaks of the curve and the wavelength gap between a maximum and a minimum is precisely of the order of d10 for a $(\sin x/x)^2$ curve.

To enable discrimination among several gratings diffracting at different wavelengths, the wavelengths corresponding to the different gratings have to be

shifted by a distance sufficient for the curves of efficiency corresponding to these different wavelengths not to get mixed up.

This is what is shown in Figure 3: it is preferably to centre the second wavelength L1 at a distance 2d10 from the first wavelength LO, then the third wavelength L2 at a distance 2d11 from the central peak of the second wavelength, etc.

If the spectral selectivity is sufficient (d10/LO sufficiently low) it is possible to discriminate among a large number of gratings with wavelengths which are close to one another, for example in a range of wavelengths of plus or minus 10% or 20% around a central wavelength. Beyond this range, it must be borne in mind that the gratings may diffract harmonic frequencies of the laser frequencies that were used for the registration and that there is therefore a risk of erroneous interpretation of a reading operation.

For example, it is possible to envisage the use of several tens of different wavelengths in a range of visible wavelengths from 0.73 micrometres to 0.87 micrometres, the wavelengths being separated from one another by gaps of the order of 0.005 micrometres, provided, however, that the selectivity is sufficient, i.e. that d10 of the curve of Figure 3 is smaller than 0.002 or 0.003 micrometres. We then have a recording system with superimposed gratings having spacings distributed, for example, between a value P-p1 and a value P+p2, p1 and p2 being of the order of 10 to 20% of P at the maximum.

To obtain the desired selectivity, the diffraction gratings should be made over a large number of spatial periods. This is why the gratings are registered in a considerable thickness of layer, for example of the order of 100 or 150 micrometres: for visible light at 0.8 micrometres and a refractive index of about 1.5, the spacing of the gratings is about 0.3 micrometres; it is therefore possible to register about 300 to 500 grating spacings in a thickness of 100 to 150

micrometres. This number enables very considerable efficiency and diffraction selectivity to be obtained.

Besides, it can be computed that the spectral selectivity d10/LO is equal to the inverse of the number of spatial periods of the diffraction grating and, consequently, for a number equal to 500 and a wavelength LO of about 0.8 micrometres, the registration wavelengths must effectively be separated by intervals of at least 2d10, i.e. at least 0.003 micrometres.

The efficiency of diffraction at the maximum of the selective curve can also be computed. It is the ratio between the intensity of the diffracted wave and the intensity of the incident beam; it is proportional to the square of the number of spatial periods of the grating (whence the importance of having sufficient thickness) and to the square of the index variation dN forming the diffraction grating. It can be estimated as being of the order of 1% or a few per cent with the orders of magnitude given above, and this is sufficient to enable detection of the presence of a diffraction grating.

With regard to the practical aspect of the reading of the optical disk, it must be noted that the procedure will use a standard movement of a reading head over tracks which contain the successive elementary zones containing the recorded data. The reading head will include the laser beam and the wide-aperture focusing objective which concentrates the beam on a very small elementary zone (1 square micrometre). Servo-linkage to a determined track will be done, for example, by etching guiding grooves in the surface of the disk, exactly as is done in disks presently marketed for the general public. The grooves may be located on the substrate of the disk, beneath the transparent layer with photo-induced index variation.

With regard to the reading laser, the making of tunable lasers is known: the frequency tuning can be done notably by variation of the temperature of the emission cavity, and finer tuning can be done by variation of the injection current for the laser diodes.

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CLAIMS

1. System for the optical recording of digital information, including a layer (16) of transparent material, in which diffraction optical gratings may be formed, the information being defined by the presence or absence, in an elementary zone (14) of the transparent layer, of a grating capable of selectively diffracting an electromagnetic radiation at a determined wavelength while diffracting scarcely or not at all the radiations at wavelengths which are strongly diffracted by other gratings, characterized in that the diffraction gratings are formed in the thickness of the transparent layer, gratings which selectively diffract different wavelengths being mixed within the thickness of the layer in at least one elementary zone (14) of the transparent layer.

2. Recording system according to Claim 1, characterized in that the layer is a layer of material with photo-induced variation in refractive index, in which the mixed diffraction gratings are recorded by local modification of refractive index according to a diffraction pattern of fringes parallel to the surface.

3. Recording system according to Claim 2, characterized in that the layer is constituted by a photopolymer capable of storing holographic type recordings.

4. Recording system according to one of the above claims, characterized in that the patterns of the different diffraction gratings have spacings distributed between a value P-p1 and P+p2, where p1 and p2 are of the order of 10 to 20% of P approximately, P being a grating spacing value.

5. Recording system according to one of the above claims, characterized in that the wavelength diffracted by a first grating differs from the wavelength closest to the first one, diffracted by another grating, by a value substantially equal to 2d1, where d1 is the distance between the first wavelength for which the diffraction by the first grating is a maximum and a neighbouring wavelength for which the diffraction by the same grating is

a minimum.

6. Recording system according to one of the above claims, characterized in that the photo-induced variation in index corresponds, for each grating, to a local variation in index that is smaller than a few per cent of the maximum variation in index that can be obtained in the material.

7. Optical recording system according to one of the above claims, characterized in that the thickness of the layer (16) is equal to at least a few tens of micrometres.

8. Recording system according to one of the above claims, characterized in that the layer (16) is formed on a plane disk (20).

9. Recording system according to one of the above claims, characterized in that it includes a mirror (18) placed beneath the layer, and a writing laser (10) that emits a beam towards the layer and through it, so that the beam combines with its own reflection, within the thickness of the layer, and therein sets up interference patterns in which the maxima of light energy are sufficient to set up permanent local variations in index in the layer.

10. System according to Claim 9, characterized in that it includes means (12) to focus the laser beam (10) on a small elementary zone of the layer, this zone having an area of the order of one square micrometre, and a depth of the order of the thickness of the layer.

11. System according to one of Claims 9 and 10, characterized in that the laser is a tunable laser.

12. System according to one of the above claims, characterized in that it includes a reading laser (22), a means (26) for the focusing of the reading laser on a small elementary zone (14) of the layer, and a means (34) for the detection of a radiation that is possibly diffracted by the layer.

13. System according to Claim 12, characterized in that it includes a semi-reflecting mirror (24) through which the laser beam (22) is

transmitted, the mirror being used to reflect a radiation diffracted backwards by the layer (16) to direct this radiation towards a photodetector (34).

14. Method for the reading of an optical disk, including the operations consisting in selecting a determined reading laser frequency from among several possible frequencies; detecting, in each elementary zone of the disk, the presence or absence of a physical pattern that is diffractive for the said frequency and not diffractive for the other frequencies, characterized in that the diffraction gratings are constituted by local variation of the refractive index within the said elementary zone, this variation being periodic in a direction essentially perpendicular to the surface of the layer.

15. Method for the writing of information on an optical disk, characterized in that several superimposed gratings of index variations are recorded in the thickness of a surface layer of the disk, made of a material with photo-induced index variation, at a given location of the layer, each grating being produced by the interference of a laser beam with its own reflection in a mirror, and each grating corresponding to a respective laser frequency different from the frequencies corresponding to the other gratings.