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(57) Abstract

There is described a method of and apparatus for improving the appearance of holographic displays reproduced from picture holograms. The method and apparatus involves the use of a holographic reflection filter (2) through which the hologram-illuminating light is filtered. The holographic reflection filter has a number of narrow passbands each associated with the frequency of the colour or colours to be reproduced by the picture hologram (3). There is described also a method of fabricating the hologram reflection filter.

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"Improvements in or Relating to Holographic Displays"

This invention relates to holographic displays, and more particularly but not exclusively relates to a method of, and apparatus for, improving the clarity, depth, and therefore the appearance of holographic displays reproduced from picture holograms. This invention also relates to procedures for fabricating a holographic reflection filter for improving the appearance of holographic displays, and to a filter produced thereby.

The sharpness of the image reproduced from a picture hologram (which may also be known as an "image hologram") is fundamentally limited by the properties of the light source used to illuminate the picture holograms, and more specifically by the size and spectral nature of the light source. This applies both to transmission picture holograms and to reflection picture holograms. For details of the definitions of "transmission holograms" and of "reflection holograms" as well as the sharpness limitations due to the properties of light sources see (for example) P. Hariharan, "Optical Holography" Cambridge University Press, 1984. This invention concerns, inter alia, the
modification of the spectral properties of light from a
light source used for illumination of a picture
hologram.

If a single-colour (monochromatic) picture hologram is
illuminated by light from a light source which has a
spectral spread greater than the spectral spread of
light naturally diffracted into the image reproduced by
the picture hologram, the quality of the reproduced
holographic image degrades at points progressively
further from the hologram plane at a rate set by the
properties of the picture hologram. If the spectral
spread of the light from the light source is modified
by being reduced below the spectral spread of the
picture hologram, for example, by the use of a bandpass
filter, this rate of image quality degradation is
reduced, resulting in improved image quality, and
allowing images with greater depth to be reproduced
with acceptable quality.

With picture holograms which are intended to diffract
more than one colour simultaneously, it is more
difficult to provide functionally satisfactory multiple
narrow wavelength filter passbands cheaply and
efficiently. A filter for such a purpose may be
prohibitively expensive to produce and it may be
difficult to achieve the necessary narrow bandwidths at
the correct pass frequencies.

According to a first aspect of the present invention
there is provided a method of improving the image
quality of a single-colour or multi-colour holographic
display reproduced respectively from a single-colour
picture hologram or from a multi-colour picture
hologram by illuminating the picture hologram with
light from a light source, said light source producing
light having a spectral spread greater than the
spectral spread of light naturally diffracted into the
image display reproduced by the picture hologram when
illuminated, said method comprising the step of
holographically filtering hologram-illuminating light
from the light source by means of a holographic
reflection filter having one or a plurality of narrow
passbands the or each of which is substantially
frequency-centred on the colour or on a respective one
of the colours to be reproduced by the picture
hologram.

According to a second aspect of the present invention
there is provided apparatus for improving the image
quality of a single-colour or multi-colour holographic
display reproduced respectively from a single-colour
picture hologram or from a multi-colour picture
hologram by illuminating the picture hologram with
light from a light source, said light source producing
light having a spectral spread greater than the
spectral spread of light naturally diffracted into the
image display reproduced by the picture hologram when
illuminated, said apparatus comprising a holographic
reflection filter interposed between said light source
and said picture hologram to filter light from said
light source to produce hologram-illuminating light,
said holographic reflection filter having one or a
plurality of narrow passbands the or each of which is
substantially frequency-centred on the colour or on a
respective one of the colours to be reproduced by the
picture hologram.

Said holographic reflection filter is preferably
constituted by a holographic filter which may be formed
as a multiple grating holographic reflection filter
preferably constituted as a planar volume holographic
reflection filter comprising multiple gratings of
appropriate different periodicities formed either in
the same volume, or formed as separate single gratings
which are either mounted close together or in optical
contact.

According to a third aspect of the present invention
there is provided a method of forming a
single-narrow-passband or multiple-narrow-passband
holographic reflection filter for carrying out the
first or second aspects of the present invention, or
for any other purpose, said method comprising the steps
of placing an initially unexposed photosensitive
proto-holographic layer in close contact with a mirror,
exposing said proto-holographic layer to a
substantially uniform collimated beam of substantially
monochromatic light having a wavelength substantially
frequency-centred on the passband or on one of the
passbands at which the filter is to operate, to cause
the incident light beam to pass through the
proto-holographic layer to be reflected by the mirror
as a reflected light beam which interferes with the
incident light beam to develop an interference grating
in said initially proto-holographic layer, said grating
having a narrow reflection band substantially
frequency-centred on the passband or on said one
passband, and (in the case where said filter is to have
multiple passbands) repeating said exposure step with
light of a different wavelength substantially
frequency-centred on a further one of the passbands at
which the filter is to operate, until said initially
proto-holographic layer records the requisite
multiple-narrow-passband holographic filter.
Said proto-holographic layer may comprise photopolymer holographic material or dichromated gelatine.

According to a fourth aspect of the present invention, there is provided a holographic reflection filter formed by the method according to the third aspect of the present invention.

According to a fifth aspect of the present invention, there is provided a hologram-illuminating light source for improving the image quality of a single-colour or multi-colour holographic display reproduced respectively from a single-colour picture hologram or from a multi-colour picture hologram by illuminating the picture hologram with hologram-illuminating light from the light source, said light source comprising a lamp producing light having a spectral spread greater than the spectral spread of light naturally diffracted into the image display reproduced by the picture hologram when illuminated, said light source further comprising a holographic reflection filter having one or a plurality of narrow passbands the or each of which is substantially frequency-centred on the colour or on a respective one of the colours to be reproduced by the picture hologram when illuminated, said filter being disposed to filter light from said lamp to produce said hologram-illuminating light.

The holographic reflection filter of the fifth aspect of the present invention may comprise the holographic reflection filter according to the fourth aspect of the present invention.

The invention thus provides (in one embodiment) a multiple grating holographic reflection filter which
has the effect of reflecting only multiple narrow bands
of desired frequencies in the spectrum of light from a
hologram-illuminating light source. The holographic
filter may be constituted by multiple separate
holograms located close together or by multiple
gratings recorded within the same medium. These
spectral passbands of the filter are substantially
matched to the desired colours to be diffracted from
the picture holograms whose images are to be reproduced
using the filter.

This form of filter and its fabrication procedure are
attractive because of the relative ease and flexibility
(compared to the prior art) with which these multiple
spectral passbands may be controlled in a reflection
holographic filter, in terms of their number,
frequency, width, and central wavelengths.

The filter of the invention is preferably constituted
as a planar volume holographic reflection filter
comprising multiple gratings of appropriate different
periodicities formed either in the same volume, or
formed as separate single gratings which are either
mounted close together or (ideally) in optical contact.
The filter is specifically for the purpose of improving
the image of a picture hologram, whether a
single-colour (monochromatic) hologram or a
multi-colour (polychromatic) hologram, by interposing
the filter between the light source and the picture
hologram, thereby modifying the spectral properties of
the hologram-illuminating light from the light source.
(In the case of a single-colour picture hologram
illuminated through the multi-colour filter, the
redundant illuminating colours do not significantly
detract from the improved quality of the single-colour
holographic image reproduced by the relevant narrow-bandwidth filtered colour).

The phrase "substantially frequency-centred" relating to wavelengths used to record holographic filters refers to the choice of recording wavelength in conjunction with the angle of incidence of the recording beams at the hologram. It is assumed that the filter is desired to operate at a specific angle and to reflect with a specific peak wavelength in the case of a single colour filter, or with multiple specific wavelengths in the case of a multiple colour filter. In order to achieve these desired replay conditions both the recording wavelength and angle are free to be chosen. However, choosing one particular wavelength for recording implicitly defines the recording angle which must be used in order to achieve the desired replay conditions for a particular passband.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:-

Fig. 1 depicts the illumination of a multi-colour picture hologram via a holographic reflection filter;
Fig. 2 illustrates a first embodiment of a holographic reflection filter, having multiple gratings with unslanted fringes;
Fig. 3 illustrates a second embodiment of a holographic reflection filter, having multiple gratings with slanted fringes;
Fig. 4 illustrates a third embodiment of holographic reflection filter, having three
single-grating reflection filters in close contact;
Fig. 5 shows the reflection spectrum of a single-passband holographic reflection filter;
Fig. 6 shows the reflection spectrum of a triple-passband holographic reflection filter having three gratings;
Fig. 7 illustrates a diffraction efficiency spectrum of an illuminated picture hologram;
Fig. 8 illustrates a method of optically recording a single-passband holographic reflection filter; and
Fig. 9 illustrates another method of optically recording a single-passband holographic reflection filter.

Fig. 1 schematically shows the use of a holographic reflection filter 2 between a light source 1 and a multi-colour picture hologram 3 to produce an image I. The picture hologram 3 may be a transmission picture hologram or a reflection picture hologram. The light source 1 may comprise, for example, a lamp, a power supply, and a reflector and/or condensing optics. The light source 1 and the filter 2 may be combined into one package providing the appropriately filtered hologram-illuminating light.

Fig. 2 schematically illustrates a vertical section of a first embodiment 2(1) of the holographic reflection filter, consisting of multiple gratings (a), (b) and (c), all of which have unslanted fringes. The gratings are recorded in superimposition in the same filter hologram 4 on a substrate 5. The gratings are protected by a coverplate 6 which may be cemented onto the filter hologram 4. This form of the filter 2 is a
feasible structure if the filter hologram 4 is recorded in (for example) silver halide, dichromated gelatin, or photopolymer material.

The fringes of the gratings need not be unslanted, and may be slanted as shown in Fig. 3, which schematically illustrates a vertical section of a second embodiment 2(2) of the holographic filter. In Fig. 3, superimposed gratings (a), (b), and (c), with slanted fringes, are formed as a hologram 7 on a substrate 8, and protected by a coverplate 9.

A third possible embodiment 2(3) of the holographic filter is schematically illustrated in vertical section in Fig. 4. The filter 2(3) comprises three single-passband grating filters 16, 17, 18 in close contact, each of these filters comprising a grating on a respective substrate. The filter 16 comprises a grating hologram 11 formed beneath a substrate 10. The filter 17 comprises a grating hologram 12 formed on a substrate 13. The filter 18 comprises a grating hologram 14 formed on a substrate 15. Each of the filter holograms 11, 12, and 14 has only a single reflection passband. The fringes of each hologram 11, 12, 14 may be unslanted or slanted relative to the surface of the respective substrate 10, 13, 15. If slanted, then additional focusing power may be included in each filter hologram.

Fig. 5 shows the intensity/wavelength graph of the reflection spectrum of a single filter such as 16 when illuminated with light having a continuous spectrum. The vertical axis of the graph of Fig. 5 is the reflection intensity R, and the horizontal axis is the spectral wavelength λ. The graph of Fig. 5 shows the
reflection spectrum to have a narrow peak of intensity
Rp centred on the wavelength $\lambda_p$, a bandwidth of $\Delta \lambda$ at
half peak intensity Rp/2, and low-intensity upper and
lower sidebands. The graph of Fig. 5 neglects the
effect of reflection from air/substrate or air/hologram
boundaries.

Fig. 6 shows the equivalent intensity/wavelength graph
of the reflection spectrum of a triple-passband
holographic filter such as depicted in Figs 2, 3, 4 and
containing three gratings with different periodicities
Corresponding to respective peak reflection wavelengths
$\lambda_1 p_1, \lambda_2 p_2, \lambda_3 p_3$. The graph of Fig. 6 neglects the
effect of reflection from air/substrate or air/hologram
boundaries.

Fig. 7 shows the intensity/wavelength graph of a
possible diffraction efficiency spectrum of a
three-colour picture hologram illuminated with light
having a continuous spectrum. The vertical axis of the
graph of Fig. 7 is the diffraction efficiency $DE$, and
horizontal axis is the spectral wavelength $\lambda$. Peak
spectral positions $\lambda_1 p_1, \lambda_2 p_2, \lambda_3 p_3$ are assumed to be
equivalent to those in Fig. 6. The width of each
spectral diffraction region is wider than the
Corresponding spectral widths of the reflection regions
of the triple-passband filter of Fig. 6. When the
image hologram of Fig. 7 is illuminated using light
filtered by the holographic filters of Fig. 6, the
resultant image spectrum is the product of the two
graphs and the spectrum of the original unfiltered
spectral light. If a uniform spectral light source is
used then, in this case, the resulting multiplying
spectrum will be similar to that of Fig. 6. Therefore,
each component wavelength band diffracted by the
picture hologram is appropriately narrowed by use of
the filter 2(3), and correspondingly the depth of a
reproduced multi-colour image will be greater at each
passband wavelength for a given subjectively acceptable
'blur'.

Fig. 8 shows a possible method of optically recording a
single-passband holographic reflection filter 24. The
method comprises the steps of placing an initially
unexposed photosensitive proto-holographic layer 20 on
substrate 19 in close contact with a mirror 21 and
exposing the layer 20 to substantially monochromatic
light of wavelength $\lambda$. The incoming light is in a
beam 22 and passes through the proto-holographic layer
20 to be reflected by the mirror 21 as a reflected
light beam 23. The incident light beam 22 interferes
with the reflected light beam 23 to develop a grating
in the layer 20, this grating having a narrow
reflection band substantially centred on the wavelength
$\lambda$.

This invention relies upon the ability of a thick
reflection grating to reflect only a limited range of
wavelengths, as illustrated in Fig. 5. The properties
of such a grating arise from its periodic structure of
alternating high refractive index regions and low
refractive index regions. In some holographic media,
such as dichromated gelatin, the ratio of reflected
power to incident power may approach unity at $\lambda p$ if
the amplitude of refractive index variation is
sufficiently large. In addition, the width $\Delta \lambda$ of the
reflection spectrum may be controlled by a number of
features, for example the thickness of the holographic
layer and the amplitude of the refractive index
variation. The wavelength $\lambda p$ of the reflection peak
may be controlled by controlling the wavelength of the light with which the filter hologram is recorded and the incidence angle of the light beam used to record the filter hologram. These are shown in Fig. 8, as \( \lambda \) and \( \theta \) respectively.

To record a multiple passband filter in one hologram, multiple exposures may be made, each with a different \( \lambda \) or \( \theta \), so as to record superimposed gratings. Bandwidths \( \Delta \lambda \) may be affected by such superimposition, so thickness and/or exposure may be altered to obtain the desired \( \Delta \lambda \).

A simple single-passband holographic filter formed as a hologram with interference planes parallel to the surface of the hologram material may be made in any suitable proto-holographic material, for example silver halide photographic film or plate, dichromated gelatin or photopolymer. An exemplary embodiment of this process is shown in Fig. 9, and is described below.

A laser beam from a laser 19 is expanded to a suitable width such that its power density does not vary significantly across the area of the hologram (ie the holographic filter) to be recorded. Laser beam expansion may be carried out by using, for example, a simple telescope 20 consisting of two lenses of differing focal lengths with a common focal point. This arrangement should provide a collimated (non-diverging) beam in the layer 21 of the proto-holographic material in which the hologram is to be recorded. The layer 21 is fixed to a transparent substrate 23 which may be of glass or Mylar (Trade Name). The substrate-mounted layer 21 is placed in contact with a mirror 22 such that the laser beam,
after passing through the layer 21 once, is reflected for a second pass through the layer 21. This reflected beam in conjunction with the incident beam provide the two interfering beams necessary to record a hologram. In addition, the fact that the mirror 22 is parallel to the layer 21 of proto-holographic material causes the resultant interference fringes to be parallel to the layer 21 (which is assumed to be a layer of uniform thickness). This parallelism is due to the fact that interference fringe planes always bisect the directions of propagation of the two interfering beams which produce the fringes.

The angle of incidence in air (θ_a) of the incident laser beam on the layer 21 defines the spacing of the fringes, according to the equation

\[ 2d \sin \theta_o = \lambda_o \]  
(1)

(derived from "Optical Holography" by R J Collier, C B Burckhardt and L H Lin (Academic Press, London, 1971), page 11), where d is the resultant fringe spacing and θ_o and λ_o are respectively the angle of incidence and wavelength both defined inside the layer 21 of proto-holographic material. θ_o may be related to the air angle of incidence, θ_a, by Snell's law;

\[ n_o \sin(90^o - \theta_o) = n_a \sin(90^o - \theta_a) \]  
(2)

where n_o and n_a are the refractive indices respectively of the medium and the air. λ_o is related to the air value of the wavelength of light, λ_a, by

\[ \frac{\lambda_o}{n_a} = \frac{\lambda_a}{n_o} \]  
(3)
These equations give the required $\theta_a$ to give a particular fringe spacing $\delta$. $\delta$ in turn is directly related to the required peak reflection wavelength of the holographic filter, given the desired angle of operation, by the Bragg relation (from page 232 of "Optical Holography");

$$2d \sin \theta = \frac{\lambda}{n_o}$$ (4)

where now $\theta$ is equivalent to $\theta_o$. Therefore, if it is wished to record a holographic filter with a peak reflection wavelength of 545nm (nanometres) at 45 degrees incidence (in air) with a refractive index in the holographic material of 1.5, the required fringe spacing can be calculated using equations 4 and 2. Equation 2 gives the internal angle, $\theta(=\theta_o)$ as 61.9°. Equation 4 then gives the required fringe spacing $\delta$ as 206 nm. If a laser wavelength of 545nm is available, then equation 1 gives the desired angle as $\theta_a = 45^\circ$.

However, if this wavelength is not available, but some other one is, such as 532nm from a frequency-doubled Neodymium-YAG laser, then to achieve a fringe spacing of 206nm, an internal angle $\theta$ of 59.4° is required, from equation 4, corresponding to an air angle $\theta_a$ of 40.2°.

The above shows the design procedure for the recording of a holographic filter for a specific peak wavelength and angle, using an available laser wavelength. Subsequent processing of the filter hologram depends on the proto-holographic material chosen. Such a holographic filter may be used directly to filter the light from a lamp in order to improve the clarity and depth of a single-colour picture hologram. Multiple
filters may be constructed and assembled as in Fig. 4
to provide the filtering action of Fig. 6 for
illuminating a multi-colour picture hologram.
Alternatively, the necessary filter holograms for
multiple filtering may be recorded sequentially within
a single proto-holographic layer as depicted in Fig. 2,
by altering recording wavelengths and angles
appropriately between exposures. Obviously this would
require the proto-holographic material to be sensitive
to all the required recording wavelengths. This is
often not the case, so the structure of Fig. 4 is
likely to be more useful.

It is possible to record holographic filters for this
application using non-collimated beams for the purpose
of including focusing power into the holographic
filters as well as including the described filtering
action.

Details of methods for environmentally protecting
holographic filters, as well as methods for determining
actual reflection spectra of reflection gratings in
holographic media, will be obvious to those skilled in
the art.

While certain modifications and variations have been
described above, the invention is not restricted
thereunto, and other modifications and variations can be
adopted without departing from the scope of the
invention as defined in the appended claims.
1. A method of improving the image quality of a single-colour or multi-colour holographic display reproduced respectively from a single-colour picture hologram or from a multi-colour picture hologram by illuminating the picture hologram with light from a light source, said light source producing light having a spectral spread greater than the spectral spread of light naturally diffracted into the image display reproduced by the picture hologram when illuminated, said method comprising the step of holographically filtering hologram-illuminating light from the light source by means of a holographic reflection filter having one or a plurality of narrow passbands the or each of which is substantially frequency centred on the colour or on a respective one of the colours to be reproduced by the picture hologram.

2. Apparatus for improving the image quality of a single-colour or multi-colour holographic display reproduced respectively from a single-colour picture hologram or from a multi-colour picture hologram by illuminating the picture hologram with light from a light source, said light source producing light having a spectral spread of light greater than the spectral spread of light naturally diffracted into the image display reproduced by the picture hologram when illuminated, said apparatus comprising a holographic reflection filter interposed between said light source and said picture hologram to filter light from said light source to produce hologram-illuminating light, said hologram reflection filter having one or a plurality of narrow passbands the or each of which is substantially frequency-centred on the colour or on a
3. Apparatus as claimed in Claim 2 wherein said holographic reflection filter is a single or multiple grating holographic reflection filter.

4. Apparatus as claimed in Claim 3 wherein said multiple grating holographic reflection filter is constituted as a volume holographic reflection filter comprising multiple gratings of appropriate different periodicities.

5. Apparatus as claimed in Claim 4 wherein said multiple gratings of different periodicities are formed in the same volume.

6. Apparatus as claimed in Claim 4 wherein said multiple gratings of different periodicities are formed in different volumes.

7. Apparatus as claimed in Claim 6 wherein said multiple gratings of different periodicities are formed as separate gratings and mounted close together.

8. Apparatus as claimed in Claim 6 wherein said multiple gratings of different periodicities are formed as separate gratings in optical contact.

9. A method of forming a single-narrow-passband or multiple-narrow-passband holographic reflection filter, said method comprising the steps of placing an initially unexposed photosensitive proto-holographic layer in close contact with a mirror, exposing said proto-holographic layer to a substantially uniform
beam of substantially monochromatic light having a
wavelength substantially frequency-centred on the
passband or on one of the passbands at which the filter
is to operate, to cause the incident light beam to pass
through the proto-holographic layer to be reflected by
the mirror as a reflected light beam which interferes
with the incident light beam to develop a grating in
said initially proto-holographic layer, said grating
having a narrow reflection band substantially
frequency-centred on the passband or on said one
passband, and (in the case where said filter is to have
multiple passbands) repeating said exposure step with
light of a different wavelength substantially
frequency-centred on a further one of the passbands at
which the filter is to operate, until said initially
proto-holographic layer records the requisite
multiple-narrow-passband holographic reflection filter.

10. A method as claimed in Claim 9 wherein said
initially unexposed photosensitive proto-holographic
layer comprises dichromated gelatin.

11. A method as claimed in Claim 9 wherein said
initially unexposed photosensitive proto-holographic
layer comprises photopolymer holographic material.

12. A holographic reflection filter when formed by the
method of any one of Claims 9 to 11.

13. A hologram-illuminating light source for improving
the image quality of a single-colour or multi-colour
holographic display reproduced respectively from a
single-colour picture hologram or from a multi-colour
picture hologram by illuminating the picture hologram
with hologram-illuminating light from the light source,
said light source comprising a lamp producing light having a spectral spread greater than the spectral spread of light naturally diffracted into the image display reproduced by the picture hologram when illuminated, said light source further comprising a holographic reflection filter having one or a plurality of narrow passbands the or each of which is substantially frequency-centred on the colour or on a respective one of the colours to be reproduced by the picture hologram when illuminated, said filter being disposed to filter light from said lamp to produce said hologram-illuminating light.

14. A hologram-illuminating light source as claimed in Claim 13 wherein said holographic reflection filter is a holographic reflection filter as claimed in Claim 12.