justifies the denomination image hologram for this kind of hologram.

Nevertheless, the thickness effect allows restitution of polychromatic images. In particular, for relatively thin emulsions and small β_0 angles, the spectral filtering is not very large. For example, for $e = 7\ \mu m$, $2\beta_0 = 25°$, $n = 1.5$, $\lambda_0 = 0.5\ \mu m$, we get from Eq. (2) $\Delta\lambda = 0.254\ \mu m$.

Thus the restituted images are no longer achromatic, as in the case of ideal image holography. However, they can be considered polychromatic. Nevertheless, the spectral filtering effect tends to increase the multiplexing capability.

To estimate storage capacity let us determine the angular selectivity of the hologram in the case of a monochromatic restitution. It can be estimated easily from the grating equation:

$$nh[\sin(\theta_1 + \Delta\theta) + \sin\theta_2] = k\lambda[1 + (1/N)],$$

where we fix the angle of observation $\theta_2 = \beta_0$.

This results in the following expression for the angular selectivity in a monochromatic restitution of wavelength λ:

$$\Delta\theta = \frac{2\lambda}{ne\sin(2\beta_0)}. \tag{4}$$

Then for a range Θ of the restitution angles, if $\Delta\theta$ is approximately considered as a constant, the number of superposable objects is given by

$$\mathcal{N}_0 = \frac{\Theta}{\Delta\theta} = \frac{\Theta ne\sin(2\beta_0)}{2\lambda}. \tag{5}$$

In the case of polychromatic restitution, the angular selectivity can be estimated from the incidence angles which give zero efficiency for the extreme wavelengths in the spectral band: $\lambda_0 \pm \Delta\lambda$.

Let us call $\beta_0 + \delta\theta$ the incidence angle giving maximum efficiency for $\lambda_0 + \Delta\lambda$:

$$\sin(\beta_0 + \delta\theta) + \sin\beta_0 = 2\frac{\lambda_0 + \Delta\lambda}{\lambda_0}\sin\beta_0. \tag{6}$$

To find the angle which makes the total efficiency zero, one must add the deviation $\delta\theta$ with the monochromatic angular selectivity $\Delta\theta$ defined by Eq. (4) for $\lambda_0 + \Delta\lambda$.

Then the total angular selectivity for the polychromatic restitution can be written as the sum of a monochromatic contribution and a polychromatic contribution:

$$\Delta\theta_{tot} = \Delta\theta + \delta\theta_{(\lambda_0+\Delta\lambda)} + \delta\theta_{(\lambda_0-\Delta\lambda)}.$$

The final storage capacity for a polychromatic restitution can then be estimated as above by calculating

$$\mathcal{N} = \Theta/(\Delta\theta_{tot}) \tag{7}$$

for each recording configuration. The corresponding numerical results are shown in Table I.

The final storage capacity is obviously lower than in monochromatic reconstruction. Nevertheless, it remains sufficiently large for several applications in which polychromatic illumination is required. The use of thicker emulsions allows an important number of objects to be stored.

Multiplexed holograms have been recorded on Agfa 8E56 holographic emulsions (7 μm thick) and on dichromated gelatins (~50 μm thick). In each case, up to three different objects have been superposed on a transmission hologram modifying the reference recording angle for an object. A restituted image is shown in Fig. 2.

To get a polychromatic restitution, we have used a 42-W white-light tungsten source. Figure 3 shows the spectrum of the source and the two image spectra from transmission holograms recorded under the same conditions ($2\beta_0 = 35°$, $\lambda_0 = 0.514\ \mu m$) on holographic emulsion and dichromated gelatin, respectively.

These measurements confirm that the spectral filtering effect remains relatively small but sufficient enough to allow multiplexing capabilities and polychromatic restitution.

Display applications often require high storage systems with polychromatic illumination. It has been shown here that use of the thickness effect in image holography allows notable multiplexing capabilities without significant degradations in the restituted images.

Such a compromise between image holography and volume holography could also be examined in the case of computer-controlled methods for the recording phase[8] to simplify the superposition of a large number of objects.

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FECO-based observations of birefringence at normal incidence in optical coatings

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Structural anisotropy[1] occurs in evaporated thin films when the condensing molecules have insufficient mobility to form a tightly packed arrangement. Shadowing causes the growth of columns which are visible in electron micrographs of thin-film sections[2] and, in the case of deposition at an angle δ, tend to grow toward the source at angle $\tan^{-1}(\frac{1}{2}\tan\delta)$.[1,3] In this Letter we discuss measurements of birefringence made at normal incidence on a number of thin-film materials which were deposited obliquely.[4]

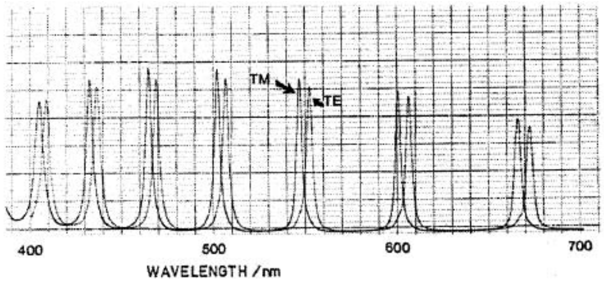

Fig. 1. Birefringence at normal incidence in a silver–silicon oxide–silver interference filter. The silver reflecting layers were deposited at normal incidence and the silicon oxide spacer layer was deposited at 60°. (Transmittance spectra recorded using polarized light).

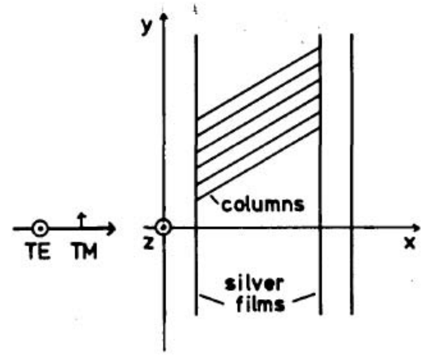

Fig. 2. TE and TM polarizations refer to the plane of incidence of the evaporant molecules. The columns which form the microstructure are also in this plane.

A typical example of birefringence is given in Fig. 1. The sample is a Fabry-Perot type metal–dielectric–metal interference filter formed by depositing silver reflecting layers at normal incidence and a silicon oxide spacer layer at 60° to the substrate normal. The traces shown were recorded in a Cary-14 spectrophotometer with glass-mounted sheet polarizers positioned in the reference and sample beams. TE and TM polarization labels (Figs. 1 and 2) refer to the plane of incidence of the evaporant molecules. For these polarization directions the transmitted peaks have minimum width and the polarization-dependent separation is a maximum.

Slight birefringence has also been observed in coatings rotated during deposition for uniform thickness; in one case a value of $\Delta\lambda \equiv \lambda_{TE} - \lambda_{TM} = 0.3$ nm was recorded for a 24-layer zirconium oxide–silicon oxide narrowband filter. This effect can be attributed to a nonzero mean deposition angle.

Moisture penetrates into voids in the layers of an optical coating during air admittance and as the coating ages in the atmosphere. As a consequence the refractive indices increase and the peaks of interference filters drift toward longer wavelengths.[5] As the uptake of moisture would be expected to decrease the magnitude of form birefringence, we measured and report typical results for birefringence in filters observed during air admittance in the regions of microscopic water penetration patches and on immersion in liquids.

A titanium oxide–silicon oxide filter of design $A[(HL)^4(H)^4(LH)^4]G$ (deposition angle 27°, O_2 pressure 3×10^{-4} mbar, substrate temperature 250°C, TiO_2 deposition rate 0.3 nm sec^{-1}, SiO_2 rate 1.0 nm sec^{-1}) yielded the following values for the wavelength of the principal transmission peak:

before air admittance, $\lambda_{TE} = 595.0$ nm,
$\lambda_{TM} = 590.5$ nm,

after air admittance, $\lambda_{TE} = 606.0$ nm,
$\lambda_{TM} = 603.5$ nm.

Thus λ_{TE} and λ_{TM} both shifted toward longer wavelengths and the difference $\Delta\lambda$ decreased by nearly 50%.

In one mode of transport water condenses at a pore and spreads laterally in the layers.[6,7] Water penetration fronts are particularly well defined in some metal–dielectric–metal filters[8] and can be observed using the method described by Macleod and Richmond.[9] Displacements in wavelength caused by the water can be measured using fringes of equal chromatic order (FECO).[10] A glass-mounted sheet polarizer located between the collimator lens and the dispersing prism of the FECO apparatus allows selection of TE and TM polarizations. A series of Ag–MgF_2–Ag filters was deposited to determine the dependence of $\Delta\lambda$ on the deposition angle δ.

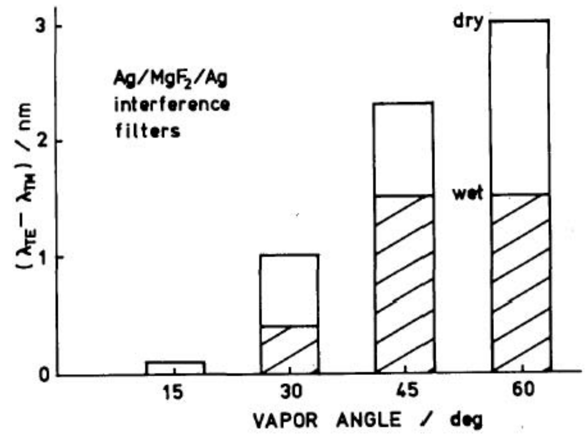

Fig. 3. Birefringence at normal incidence in silver–magnesium fluoride–silver interference filters measured in wet regions (microscopic water penetration spots) and surrounding dry areas. The value of $\lambda_{TE} - \lambda_{TM}$ is reduced by the water which penetrates into the magnesium fluoride spacer layers.

The results of measurements made on wet and dry areas of the filters using the FECO method are given in Fig. 3.

Immersion in water or ethanol also reduces the value of $\Delta\lambda$. In one experiment a zirconium oxide–silicon oxide filter of design $A[(HL)^5(H)^4(LH)^5]G$ (deposition angle 27°, O_2 pressure 3.8×10^{-4} mbar, substrate temperature 280°C, ZrO_2 deposition rate 0.4 nm sec^{-1}, SiO_2 rate 1.0 nm sec^{-1}) was placed in a cell containing water and spectrophotometer measurements showed that $\Delta\lambda$ decreased from 4.0 to 2.3 nm. The FECO method applied to the same sample, this time using a thin layer of water between the filter and an optically flat cover plate, gave values of 4.0 and 2.0 nm. Refractive-index oils did not penetrate into the voids in the layers, presumably due to the larger size of the molecules. Some of the moisture which enters a coating can be removed[11] by heating or desiccation in vacuum, for example. When water was pumped from a silver (0°)–cryolite (45°)–silver (0°) filter, $\Delta\lambda$ increased from 0.3 to 0.7 nm.

All measurements on wet and dry areas of filters gave the result $\lambda_{TE} > \lambda_{TM}$, whereas the birefringence predicted by an elementary film model of parallel tilted cylindrical columns of circular cross section is positive uniaxial giving $\lambda_{TE} < \lambda_{TM}$. Our measurements indicate that a biaxial model is required for films deposited obliquely. Additional measurements which have been made using off-axis optical probe beams support the notion of a biaxial model and allow the principal indices of refraction to be estimated.[12] For modest angles of deposition the difference between the two models is small and significant only for optical measurements made near normal incidence.

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Meetings Calendar

1985

June

5–7 Local Area Networks course, Atlanta *Data-Tech. Inst., Lakeview Plaza, P.O. Box 2429, Clifton, N.J. 07015*

6 Testing/Measurements for Fiber Optics course, Boston *Communications & Info. Inst., c/o Info. Gatekeepers, Inc., 214 Harvard Ave., Boston, Mass. 02134*

9–13 Soc. for Experimental Stress Analysis Spring Mtg., Las Vegas *SESA, 14 Fairfield Dr., Brookfield Ctr., Conn. 06805*

10 Fiber & Integrated Optics course, Wash., D.C. *J. Perkins, Geo. Wash. U., School of Eng. & Applied Science, Wash., D.C. 20052*

10–12 Local Area Networks course, New York *Data-Tech Inst., Lakeview Plaza, P.O. Box 2429, Clifton, N.J. 07015*

10–13 Short Wavelength Laser Systems course, Dallas *Eng. Tech., Inc., P.O. Box 8859, Waco, Tex. 76714*

10–13 **Int. Lens Design, OSA Tech. Mtg.,** Cherry Hill *OSA Mtgs. Dept., 1816 Jefferson Pl., N.W., Wash., D.C. 20036*

10–14 Fiber & Integrated Optics course, Wash., D.C. *Contd. Ed. Program, Geo. Wash. U., Wash., D.C. 20052*

10–14 IMAGE '85, Helsinki *P. Oittinen, Helsinki U. of Tech., Lab. for Graphic Arts Tech., Tekniikantie 3, 02150 Espoo 15, Finland*

10–14 **OSA Spring Conf.,** Cherry Hill *OSA Mtgs. Dept., 1816 Jefferson Pl., N.W., Wash., D.C. 20036*

10–14 Lasers, Microwaves, Ultraviolet, Magnetic Fields, & Ultrasound: Biophysical & Biological Basis, Applications, & Hazards in Medicine & Industry course, Edinburgh *Off. of Summer Session, Rm. E19-356, MIT, Cambridge, Mass. 02139*

10–14 Chemically Modified Electrode Surfaces: Preparation, Characterization, & Applications course, Edinburgh *Off. of Summer Session, Rm. E19-356, MIT, Cambridge, Mass. 02139*

10–14 Robot Manipulators, Computer Vision & Intelligent Robot Systems course, Edinburgh *Off. of Summer Session, Rm. E19-356, MIT, Cambridge, Mass. 02139*

10–14 Using the ADA Programming Language course, Ann Arbor *Eng. Summer Confs., 200 Chrysler Ctr., N. Campus, U. of Mich., Ann Arbor, Mich. 48109*

10–14 Applied Numerical Methods Using Personal Computers course, Ann Arbor *Eng. Summer Confs., 200 Chrysler Ctr., N. Campus, U. of Mich., Ann Arbor, Mich. 48109*

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