

Planar spectroscope or continuous-spectrum hologram based on self-organizing TE-gratings

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A planar spectroscope is an optical device that combines in one plane its dispersive function and its ability to image a spectral line. These are the inherent properties of the variable-period grating,¹ called a frequency multiplexor, and also of the Lippmann color photograph,² if the method is used to photograph the continuous spectrum in a spectrograph. The Lippmann photograph can be regarded as the hologram of the spectrum when the object wave is the spectral image of the spectrograph slit and the reference wave is the reflected wave. Leaving on one side the question of the quality of the spectral image of the slit, we shall take account of only the basic possibility of producing a planar spectroscope by these methods. The goal of this note is to report a new method of producing a hologram continuous spectrum.

It has been known since 1984 that spontaneous periodic structures (SPS) are formed in AgCl thin films illuminated by linearly-polarized visible radiation from continuous-wave gas lasers.^{3,4} The SPS are due to the waveguide properties of such films, and are formed as a result of interference between the incident beam and radiation scattered by the waveguide TE-modes. The SPS begin to evolve on the initial interference patterns near small Rayleigh-type scattering centers, and their subsequent development is determined by positive feedback that arises as a result of the greater mode input into the film with the initial SPS. These ideas about the nature of SPS have been confirmed quantitatively by using the phase locking relation for the propagation vectors of the SPS, the mode, and the incident wave \mathbf{K} , β , and \mathbf{k} respectively:

$$\mathbf{K} = \bar{\beta} - \mathbf{k}_x, \quad (1)$$

where $k_x = k \sin \varphi$, $k = 2\pi\lambda_0^{-1}$, λ_0 is the incident wavelength, and φ is the angle of incidence of the laser beam on the film. For the TE_m modes, $\mathbf{K} \perp \mathbf{E}_0$ (\mathbf{E}_0 is the beam polarization vector), $|\mathbf{K}| = 2\pi d^{-1}$ (d is the period of the SPS in the plane of the film), and β is found from the dispersion relation

$$khp = \arctg \frac{(n_1^2 - 1 - p^2)^{1/2}}{p} + \arctg \frac{(n_1^2 - n_2^2 - p^2)^{1/2}}{p} + m\pi, \quad (2)$$

where h is the film thickness, $p = (n_1^2 - \beta^2 k^{-2})^{1/2}$, n_1, n_2 are the refractive indices of the film and the substrate, respectively, and $m = 0, 1, 2, \dots$

Electron microscopy of the SPS has shown⁴ that these structures are imperfect diffraction gratings which consist of subgratings-domains that develop on different scattering centers. The small SPS period ($\lambda_0 n_2^{-1} \gg d > \lambda_0 n_1^{-1}$) and the small size of the domains (a few μm) show that low-coherence nonlaser radiation can also produce the SPS. Indeed it was shown later⁵ that the SPS were formed when the film

was exposed to the spectral components of the radiation emitted by a gas-discharge mercury lamp. However, the possibility of the SPS being inscribed by continuous-spectrum radiation has remained an open question. The main difficulty in this type of experiment has been the low optical sensitivity of the film and the necessity for long exposure ($H \approx 1 - 10$) J/cm². For such H and using conventional light sources, the necessary exposure times can be up to several hours. Such experiments are nevertheless of methodological interest because they enable us to demonstrate that it is possible to produce continuous-spectrum holograms with the aid of self-organizing TE_m-gratings.

In our experiment, the white-light source was a gas-discharge xenon lamp (type DKsSh-150) whose emission was focused on the slit of the spectrograph by spherical and cylindrical lenses (the latter was used to stretch the image along the slit). We used a small spectrograph incorporating an Abbe prism (dispersion 15 nm/mm and spectral slit width 3 nm near $\lambda_0 = 550$ nm).

The AgCl film was evaporated in vacuum on to a glass substrate (20 × 30 mm²) and a silver film (≈ 10 nm) was deposited on top of it. The measured thickness of the AgCl-Ag combination was 118 nm. The AgCl film acquires a characteristic hue when the silver film is deposited upon it, which signals the formation of fine colloidal particles of Ag and AgCl. The colloidal absorption band with a peak near $\lambda_0 = 510$ nm extends over the entire visible aprt of the spectrum. The optical sensitivity of the sample is determined by the interaction of light with the colloid in the AgCl matrix.⁶

The AgCl-Ag film prepared in this way was mounted in the focal plane of the spectrograph and was exposed to the unpolarized spectrum. Observations of the optical properties of the film in the course of the exposure showed that a 5–10 min exposure is sufficient to give rise to appreciable photoadaptation⁷ (i.e., the film acquires, in transmission, the hue of the incident light). This photoadaptation is due to the deformation of the colloidal band by the incident light, which results in reduced absorption near λ_0 . Photoadaptation also gives rise to a reduction in the attenuation of scattered waveguide modes and the gradual onset and evolution of the SPS that are already detectable in the blue-green after about 1 h of exposure. The SPS diffraction efficiency η decreases with increasing H , and they gradually evolve at progressively lower values of λ_0 . The evolution of the SPS was monitored visually by looking at diffraction patterns in reflected light, with illumination turned off and the grating exposed to light from a hot-filament lamp or a mercury discharge lamp, at an angle in the plane of incidence parallel to the slit. It is interesting to note that the SPS evolved preferentially along the slit ($\mathbf{K} \parallel \text{slit}$). The slight polarization of the radiation by the spectrograph had practically no effect on the direction of \mathbf{K} . When \mathbf{K} was perpendicular to the slit, i.e.,

when the effect was observed along the spectrum, the efficiency η was found to be significantly lower. The anisotropy in the evolution of the SPS can be explained by the fact that modes scattered along the slit and corresponding to different λ_0 within the slit spectral width, show virtually no competition, whereas competition does occur in the direction of increasing wavelength, and slows down the evolution of the gratings. The exposure of the sample was terminated ($t \approx 10$ h) when the diffracted light from the mercury discharge lamp contained the green (546 nm) and yellow (578 nm) mercury lines in positions on the film that were expected under exposure to the continuous spectrum (Fig. 1).

The formation of the SPS for different λ_0 can be looked upon as the holographic record of the spectral images of the slit for which the waveguide modes are the reference waves. This type of hologram is a kind of multiplexor in which the parameter d of gratings with \mathbf{K} parallel to the slit varies over the spectrum in accordance with the dispersion of the spectrograph. White radiation parallel to \mathbf{K} must be introduced into the film to reproduce the spectrum exactly. However, this is not possible in practice since the film is not a good waveguide because of strong mode attenuation, especially in its unexposed parts. It is therefore more convenient to observe the recorded spectrum under external illumination and value of φ for which the reproduced spectrum corresponds to the original spectrum. Because η is low, a bright image is observed for intense sources. Since the exposed AgCl-Ag film retains its light sensitivity, illumination by high-intensity light gradually destroys the hologram. For long-term storage and demonstration, the specimen must be treated with a fixer that dissolves AgCl, while the silver that forms the SPS remains on the substrate. To increase η in reflected light, the sample is then coated with an aluminum film. These operations do not affect the magnitude of d for the remaining SPS, which retains its initial value. The photograph reproduced in Fig. 1 shows the final specimen illuminated with light from a mercury lamp at an angle of incidence $\varphi \approx 70^\circ$ and observed at $\varphi \approx 59^\circ$. A photograph of the SPS was also taken in an electron microscope for a fixed sample corresponding to $\lambda_0 \approx 550$ nm (Fig. 2). At first sight, the SPS appears to be an irregular net, which should be the case for unpolarized light.⁵ However, when the photograph is viewed at a large angle of incidence and at different azimuths, it is readily seen that the vector \mathbf{K} has a preferred direction for linear microgratings with $d \approx 312$ nm.

The main properties of the hologram obtained in this way are determined by the dependence of d on λ_0 . Measurements of the function $d(\lambda_0)$ were performed in the beam of a N_2 laser ($\lambda = 337$ nm) with the specimen mounted in a holder on the goniometer. The spacing d was found from the measured φ for which the diffracted beam was observed in reflected light on a luminescent screen in the direction oppo-



FIG. 1. Photograph of spectral lines of Hg (yellow, green, and blue) produced in reflection by the planar diffraction spectrograph.

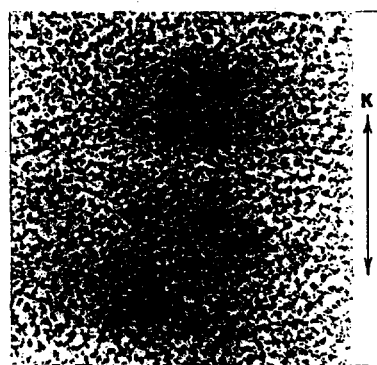


FIG. 2. Electron microscope photograph of the SPS produced when the AgCl-Ag film was illuminated with $\lambda_0 = 550$ nm light. Arrow shows the predominant direction of \mathbf{K} in the microgratings.

site to the direction of incidence, in which case $d = \lambda (2 \sin \varphi)^{-1}$. On the other hand, $d(\lambda_0)$ was calculated from (1)–(2) for known h , n_1 , $n_2 = 1.515$. We took into account the dispersion of n_1 for AgCl (Ref. 8) and the deviation from normal incidence when the film was exposed to different λ_0 (Fig. 3). The discrepancy between experimental and calculated points is particularly large for $\lambda_0 < 500$ nm and is due to the fact that we have ignored the anomalous dispersion of the effective n_1 in the colloidal band of silver. For $\lambda_0 > 550$ nm, the experimental result is almost linear, which is the reason why the observed spectrum matches well the original spectrum (Fig. 1). For $\lambda_0 < 500$ nm, d is a slower function of λ_0 which (especially if we take account of grating imperfections) leads to the broadening of the diffracted spectral line (cf. Fig. 1; $\lambda = 436$ nm).

These results show that AgCl-Ag films can be used as a basis for a planar spectrograph that satisfactorily reproduces the spectrum of strong sources in the red-green range. It can be employed in teaching as an example of the use of spontaneous waveguide scattering in a thin film as a means of recording the spectrum, and also as an individual demonstra-

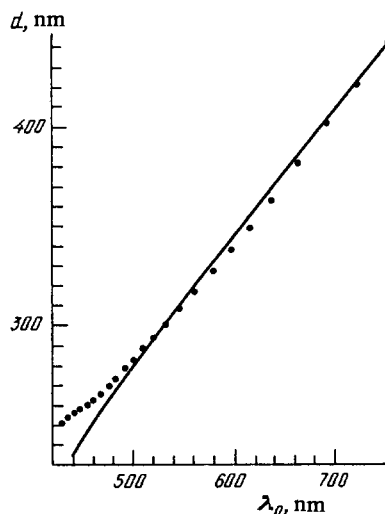


FIG. 3. The SPS period d as a function of λ_0 . Solid line—calculated from (1)–(2); points—experimental.

tion spectroscopy. Other photosensitive films^{9,10} can also be used to record the SPS, but in narrower spectral ranges. The AgCl–Ag films are unique from the point of view of the wavelength range of their spectral sensitivity. The quality of the hologram can be improved by using stronger sources, linearly-polarized radiation, and a grating spectrograph with linear dispersion that is small and constant over the spectrum.

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