

THERMOPLASTIC FILM CAMERA FOR HOLOGRAPHIC RECORDING

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ABSTRACT

The design thermoplastic-film recording camera and its performance for holography of extended objects are reported. Special corona geometry and accurate control of development heat by constant current heating and high resolution measurement of the develop temperature make easy recording of reproducible, large aperture holograms possible. The experimental results give the transfer characteristics, the diffraction efficiency characteristics and the spatial frequency response.

1. INTRODUCTION

Usually, an optical recording medium requires a certain processing to transform the recorded information into a form that is suitable for readout. In some applications, like Optical Memories (1), Optical Information processing (2) and Holographic Interferometry (3), this processing should be preferably done inside the recording configuration. In industrial applications, e.g. of the holography, the processing time should be as short as possible.

The conventional silver halide emulsions do not meet these requirements. Their processing, consisting of wet chemical development and fixation, usually can not be accomplished in the recording setup. A repositioning of the processed plate of film into the optical setup with an accuracy up to some fractions of the optical wavelength is very critical, and troublesome.

In the past two decades, this limited potentiality of conventional photographic materials has brought many investigators to explore the possibilities of new types of recording media. It was shown that the use of photothermoplastic materials for recording offers significant advantages due to the combination of the following properties of thermoplastic materials :

1. A considerably low value of the exposure energy is needed.
2. The diffraction efficiency is rather high.
3. The recording of information and processing for readout can be done in situ, so that no repositioning troubles are met.
4. If desired, the recorded information can be erased, and the material is then reusable for the next recording.

Experiments with a thermoplastic material on a glass carrier for information storage have started as early as 1959 (4). In the recent time a photothermoplastic film with a plastic carrier was developed, which is better suitable for industrial applications than the plate. Also cameras using the photothermoplastic film were introduced.

Nevertheless, some further optimization of this recording technique and the instrumentation are still necessary, to make them useful for high repetition rate laboratory experiments, for industrial applications and for difficult holographic recordings with large aperture.

## 2. PHOTOTHERMOPLASTIC FILM

The photothermoplastic film (e.g. Kalle PT-1000) consists of three layers (5). On the transparent plastic carrier a thin photoconductive layer is deposited, which is covered finally by a thin layer of the thermoplastic material.

For sensitizing the film, the surface of thermoplastic material is uniformly electrically charged. During the recording, the intensity distribution of the incident light produces a conductivity pattern in the photoconductive layer which results in a charge redistribution on the surface of the thermoplastic material. The surface-charge distribution produces finally a pattern of electrostatic forces in the thermoplastic material which is a replica of the light-intensity pattern to be recorded.

To develop the force pattern, the thermoplastic material has to be heated slightly above its melting point. Becoming soft, the surface is deformed under the influence of the electrostatic forces until at each point an equilibrium between the surface tension forces and the electrostatic forces is obtained. Being cooled down under the melting temperature, the thermoplastic material hardens again and the surface deformation becomes fixed. The surface of the developed film becomes slightly milky as if frosted.

To perform the phase transition of melting, a certain amount of heat must be delivered to the thermoplastic layer. This has to be done rather quickly to avoid surface charge loss due to conductivity of the thermoplastic material which rises drastically near the melting point. To obtain a fast softening, the material is heated for a short time far above the real melting temperature to pump the necessary develop heat into the thermoplastic layer in a very short time.

To reconstruct the information, now stored in the form of the thickness variation of the thermoplastic, the film is illuminated with a readout laser beam. The phase of this beam will be changed according to the stored thickness variation, which corresponds to a phasehologram.

When heated beyond the melting temperature, the thermoplastic material softens so far, that the stored information is erased. Theoretically, the film could be used after cooling for a next record. This is nevertheless not recommendable due to successive degradation of the thermoplast layer and to possible ghost pictures due to imperfect erasing.

To obtain a homogenous film sensitivity across the whole active area, the surface charge has to be perfectly uniform. According to theoretical predictions (6), the sensitivity of the film depends at least quadratically on the electric field or the charge density. Usually, the surface has to be charged to several hundreds of volts. The easiest way to do it is by means of a corona discharge in air.

## 3. CAMERA

The camera consists of a mechanical body and of an electronic control unit. The mechanical arrangement and the functions of the camera body are based on the well proven principles and the design as described by R. Moraw (5). We have optimized our camera especially for industrial applications of holographic interferometry. The recording aperture of the camera is 70 x 50 mm. The method we use consists of successive stages of charging, exposure and development.

In the mechanical body, the thermoplastic film is stretched across a carrier plate, made of insulating material. A glass plate with a vacuum deposited, transparent resistive layer on the surface is embedded in the carrier plate in such a way, that the film is guided exactly along its coated surface. The resistive layer on the plate is equipped with contacts in the form of thicker, vacuum deposited conductive strips along two parallel edges of the plate. Two thick copper mesh strips are pressed by rubber cushions against these plate contacts. One of the plate contacts is grounded.

During the sensitizing phase, a carriage with a linear array of needles for corona charging is slowly moved at a constant distance along the film surface. The static charge on the film provides also for its firm adhesion on the glass. For film transport, the carriage lifts the adhering film from the surface of the glass plate and a motor-winder transports the film.

To assure a perfectly uniform charge distribution on the film surface and thus a uniform sensitivity across the film area, a relatively dense linear array of needles with a precisely defined radius has to be used. We found as an optimum a radius of 0.2 mm and a separation of 2.5 mm. The array has to be somewhat longer than the film-width to reduce edge effects. The peaks of the needles have to be adjusted to lie exactly on a straight line. The distance of the peaks to the thermoplastic surface has to be optimized for a given voltage to allow for homogenous charge distribution without any charge concentration in the central part of the film area and to prevent local break downs.

Massive breakdowns would damage the transparent resistive layer on the glass, if the output capacitor of the HV power supply could be discharged into the thin layer without a current limitation. To minimize this damage, a HV resistor of several tens of megaohms is inserted into the lead from the HV power supply to the array of needles on the carriage.

After sensitizing, a waiting time of several seconds is necessary before exposure, to allow the mechanical vibrations of the whole camera body to die away.

For development, a current puls is fed to the resistive layer on the glass plate, which acts as a resistive heater and simultaneously as a resistive temperature sensor, allowing to measure the temperature of the heater and to turn off the heating at the appropriate moment. The temperature coefficient of the optically transparent resistive layer (Balzers Aurell-A3) is nevertheless very low, about +600 ppm/deg C. To measure the turn-off temperature accurately, a high resolution resistance bridge is needed.

Fig.1 shows the simplified circuit diagram of the electronic development control, we use successfully in our photothermoplastic cameras.

The resistance  $R_p$  of the heater builds together with a shunt  $R_s$  and the resistors  $R_{11}$ ,  $R_{21}$ ,  $R_{12}$ ,  $R_{22}$  (SW3 open) a Thomson bridge, which eliminates errors due to the resistance of the wiring. The value of  $R_s$  is 2 Ohms, the other resistors are kOhm values, being 1000x larger than  $R_p$  and  $R_s$ . The copper mesh strips are connected on one side to the development-current source, the opposite ends are connected to the bridge circuit.

The bridge circuit, adjusted for balance at  $T_d$ , is used to detect the achievement of the develop temperature  $T_d$  and to turn off the heating current. It should be mentioned here, that the develop temperature  $T_d$  should not be understood as the softening temperature of the thermoplastic material, but rather as the heater temperature at which heating is to be turned off.

With a new heater plate inserted, the bridge has to be pre-balanced first, as the heater resistance has a manufacturing tolerance of some +/- 20 % around the nominal value of 15 ohms.

A floating voltage source source PS2 of a few volts is used to feed the bridge without causing a significant warmup of the heater during the balancing (SW2 closed, SW3 open, T1 nonconducting). With SW3 open, the bridge is balanced if

$$R_p(T_a)/R_s = R_{11}/R_{12} = R_{21}/R_{22}$$

where  $R_p(T_a)$  stands for the heater resistance at the ambient temperature  $T_a$ , at which the bridge was balanced.

The setting of the resistances  $R_{11}$  and  $R_{21}$  is ganged for proper balancing of the bridge. Each resistance is a series combination of low temperature coefficient (15 ppm/deg C) precision resistors, which are switched in steps and of a helipot potentiometer. The precision comparator C (e.g. a uA 734) and a light emitting diode LED serve a a balance indicator.

At the develop temperature  $T_d$ , the value of  $R_p$  will be

$$R_p(T_d) = R_p(T_a) \cdot \{1 + k (T_d - T_a)\}$$

where  $k$  stands for the temperature coefficient of the heater layer.

To obtain balance at  $T_d$ , the value of  $R_{12}$  is decreased (SW3 now closed, potentiometer  $R_{112}$  in parallel to  $R_{12}$ ) to

$$R_{12}' = R_{12} / \{1 + k (T_d - T_a)\}$$

where  $R_{12}'$  is the parallel combination of  $R_{12}$  and  $R_{112}$ ,

$$R_{12}' = R_{12} \times R_{112} / (R_{12} + R_{112})$$

A slight mismatch in the ratio  $R_{21}/R_{22}$  ( $R_{22}$  not being changed correspondingly with  $R_{12}$ ) decreases marginally the suppression of the wiring resistance ; this effect is of no importance, as the resistance change of  $R_p$  between  $T_a$  and  $T_d$  is very small.

The correct setting for  $T_d$  can be hardly calculated, as the necessary temperature overshoot for development depends on many parameters like rate of temperature change, thickness of the film carrier layer etc ... Thus, the setting for  $T_d$  has to be found experimentally. Once found at any ambient temperature  $T_a$ , it keeps valid for any initial conditions of the heater temperature.

The bridge circuitry and the comparator are placed in a screening box in the camera body. Besides that, the camera body contains a remote controlled HV power supply for the corona charging. All other circuitries are placed in the electronic control unit, which is connected to the camera body by a cable.

From the control unit, only the development-current source in shown in a simplified form in Fig.1. A floating power-supply PS1 charges over a current limiting resistor  $R_1$  the electrolytic capacitor  $C_1 = 72,000 \mu F$  to 140 volts. A constant-current circuit, consisting of transistor T1, resistor  $R_2$  and a Zener diode ZD1 can deliver between 5 to 6 Amps into the heater plate. The current source can be turned on and off by the set-reset flip-flop F-F which controls the optocoupler O.C. and the transistor T2 (both saturated or off). The collector current of T2 feeds the Zener diode ZD1 and turns thus T1 on.

For development, the flipflop F-F is set by a short puls to turn on the heating. The bridge remains unbalanced and the comparator output high, until  $T_d$  is reached. Then the comparator resets the flipflop and terminates the heating.

With a constant heating current, the rate of change of the thermoplast temperature is also approximately constant. Obviously, the higher the rate of change of the temperature of the heater, the larger will be the lag in the rise of the temperature of the thermoplast itself, as the heat is transferred from the heater to the thermoplast by conduction through the film carrier and the photoresistive layer. At the moment, when the thermoplast reaches its melting temperature, the heater has already a temperature overshoot due to the mentioned lag and naturally some amount of heat is stored in other components like glass plate etc ... All these overshoot effects can be compensated by a proper setting of the develop (turn-off) temperature  $T_d$ . With different initial conditions of temperature, the duration of the heating puls will vary, but the develop heat will remain constant.

In the practical circuit, 5 transistors 2N6259 with separate emitter resistors are used in a Darlington stage as T1, to prevent second break-down if a short-circuit across the load should occur. As the capacitor C1 contains only a limited amount of energy, no thermal destruction of the camera could occur even if the electronic switch should fail to open due to some defect in the circuitry. On the other hand, the capacitor must be large enough, to allow to keep the heating current constant until the end of the development, i.e. under typical laboratory conditions between 100 and 400 msec.

The electronic control unit controls also all other camera functions.

During the sensitizing phase, the film transport and corona charging is controlled. The corona voltage  $V_c$  can be preset in the range between 5 kV and 15 kV.

A shutter control allows for a time preset between 50 msec and 5 sec or for a permanent opening of the shutter. For a optimum reproducibility of the holograms, we use an integrating exposuremeter with energy preset for the shutter control (7).

The preset of the develop temperature is done with a helipot potentiometer in the control unit.

After the dry thermal development, a cooling timer with a time preset between 20 sec and 500 sec is started automatically. The fixation of the hologram can be done either by ambient air only, or by forced cooling. In the latter case, a set of fringes may arise due to shrinking effects.

As any running function inhibits automatically a start of any other function, repeated attempts of development in short time intervals, which could damage the plate are also disabled.

We use the same electronics for the large aperture camera of 70 x 50 mm and also for the small aperture camera of 35 x 50 mm. For the small aperture camera only, a capacitor C1 of 24,000  $\mu$ F is sufficient ; only 3 power transistors are needed as T1 and the heating current can be reduced to 4 to 5 Amps.

#### 4. EXPERIMENTAL RESULTS

The experimental results are shown for the use of this thermoplastic film camera in an holographic system. Three tests have been chosen : (1) the transfer characteristics ; (2) the

diffraction efficiency characteristics ; and (3) the spatial frequency response.

Holograms of a diffusely illuminated two-dimensional object were made with approximately 21 deg angle between the object beam and the reference beam R1 and 24 deg for the reference beam R2. The recording and reconstruction wavelengths for all results presented in this paper were 514.5 nm and were recorded with the optical setup shown in Fig.2. In our experiments we used PT 1000S (8) photothermoplastic films with 35 x 50 mm and 70 x 50 mm as recording aperture.

Fig.3 shows the curve of brightness in the reconstructed image as a function of exposure for holograms of a diffused object. The exposure sensitivity of the film is high and comparable to that of high resolution photographic emulsions. We observed that increasing the potential to which the thermoplastic surface is charged tends to move the curve to lower exposures as predicted theoretically by Gaynor (6). The maximum occurs at an exposure of about 0.8  $\mu\text{J}/\text{cm}^2$ .

The most critical factor at the development stage is the thermoplastic develop heat. As mentioned above, this heat is determined primarily by the rate of change of temperature during the heating and by the develop temperature  $T_d$ , at which the heating is turned off. This turn-off temperature is always higher than the melting temperature of the thermoplastic, as the melting heat has to be delivered to the thermoplastic in a very short time during this temperature overshoot. With different initial conditions of temperature, the duration of the heating puls will vary, but the develop heat will remain constant.

The dependence of the brightness of the reconstructed image on the develop temperature is given in Figs.4 and 5. These results, especially the one in Fig.4, show clearly that the reproducibility in the brightness of the reconstructed image of thermoplastic holograms depends very strongly on the develop heat and thus also on the develop temperature  $T_d$ . On the other hand, the Fig.5 shows, that the duration of the heating puls has no significant influence on the brightness, as expected. A deviation of  $\pm 0.5$  deg C from the optimum develop temperature results typically in a decrease of the brightness of the reconstructed image by 25 %.

The constant-current heating controled by a direct measurement of temperature allows to keep the develop temperature and thus also the develop heat reproducibly within a narrow limit independent of ambient temperature variations or undefined initial thermal conditions of the heater at repetition rates with intervals below 5 minutes. This results in only  $\pm 5$  % variation in brightness of the reconstructed image.

The specially designed corona geometry allows to improve the homogeneity of the efficiency over the recording frame. We have experimentaly found that the variation of the efficiency over the recording area (70 x 50 mm) is about  $\pm 2$  %.

In order to measure the signal-to-noise ratio (SNR), we utilized as the object a white painted surface whose central part was covered with an opaque strip. The SNR was determined by scanning the reconstructed real image with a pinhole-photomultiplier tube assembly and by computing the ratio of the averaged intensities across the illuminated and the opaque part of the image. The result is given in Fig.3 and is obtained at a spatial frequency of 650 L/mm with the corona voltage  $V_c$  of 14.5 kV and a reference-to-signal beam ratio of 1. In Fig.6 the brightness in the reconstructed image at a spatial frequency of 650 L/mm is shown

as a function of the beam ratio. The maximal brightness in the reconstructed image is not coincident with the highest SNR.

To determine the diffraction efficiency we recorded holograms with a setup shown in Fig.2. Diffraction efficiency is the percentage of the incident light diffracted into the first order by the hologram. The maximum diffraction efficiency we achieved with PT 1000S for a diffused object was about 30 % at a spatial frequency of 600 L/mm as it is shown in Fig.7.

In our holographic experiments with the PT 1000 type thermoplastic film we obtained for a diffuse object a band-pass response for spatial frequencies with a maximum at 550 L/mm and a useful range from 350 to about 900 L/mm as shown in Fig.8, where  $I_o^*$  (NORM) is the distribution of the brightness in the reconstructed image divided by the light distribution of the illuminated object. For these measurements, the same pinhole-photomultiplier tube assembly is used. Short exposure times lead to additional suppression of the higher frequencies. The knowledge of this response allows to estimate the maximum size of a recordable object as well as to design a special object illumination which compensates for the intensity losses at higher frequencies.

## 5. CONCLUSIONS

The thermoplastic recording medium has a considerable potential for many holographic applications. It offers ease and convenience to the rapid in situ process of recording and reconstructing of large aperture holograms.

The panchromatic and sensitive photoconductor gives the medium a response comparable to that of high resolution photographic emulsions. Furthermore, the thermoplastic forms relatively efficient thin phase holograms. The holograms can be formed over a broad range of exposures, but are much more sensitive to the develop heat. Although the sensitivity to the develop step is an inconvenience, it is relatively straightforward to use the constant-current resistive heating and a direct measurement of the heater temperature for an accurate develop heat control. Finally the addition of a special designed corona geometry permits rapid and uniform charging.

The investigations show that the performance of a thermoplastic film camera can be optimized to such an extent that even difficult holographic recordings with large apertures, e.g. as needed for industrial applications of dual reference-beam holography (9) and heterodyne holography (10), can be made in a routine manner.

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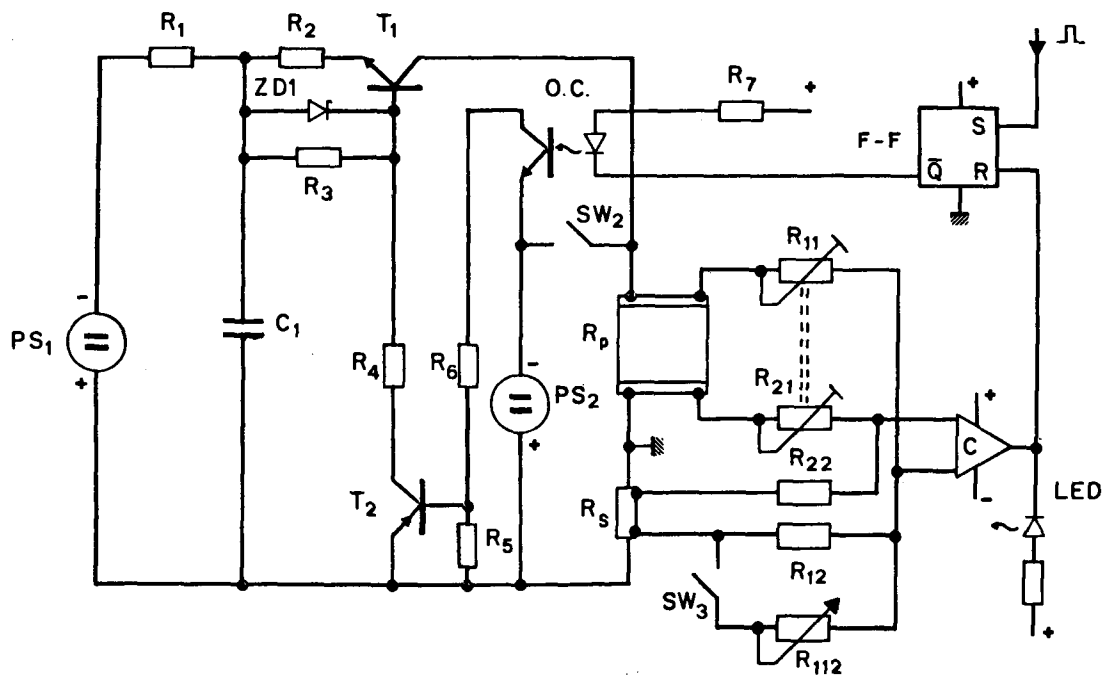


Fig. 1 Simplified circuit diagram of the development control



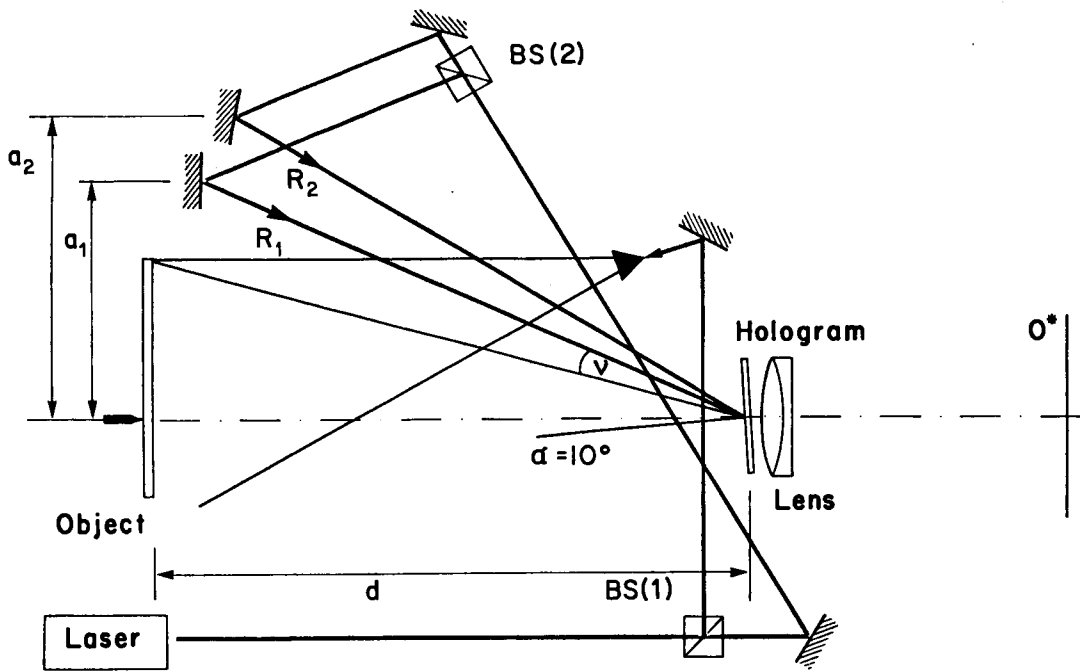


Fig. 2 Holographic set-up for the measurements of transfer characteristics, diffraction efficiency and spatial frequency response

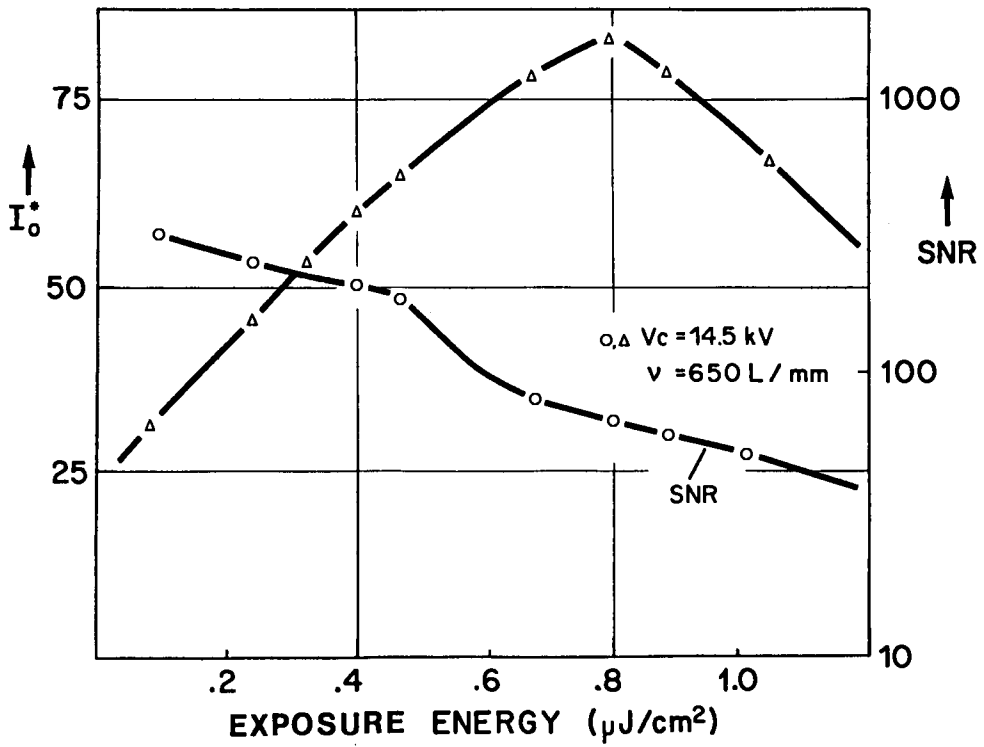


Fig. 3 Curve of brightness and SNR in the reconstructed image of thermoplastic holograms as a function of exposure energy

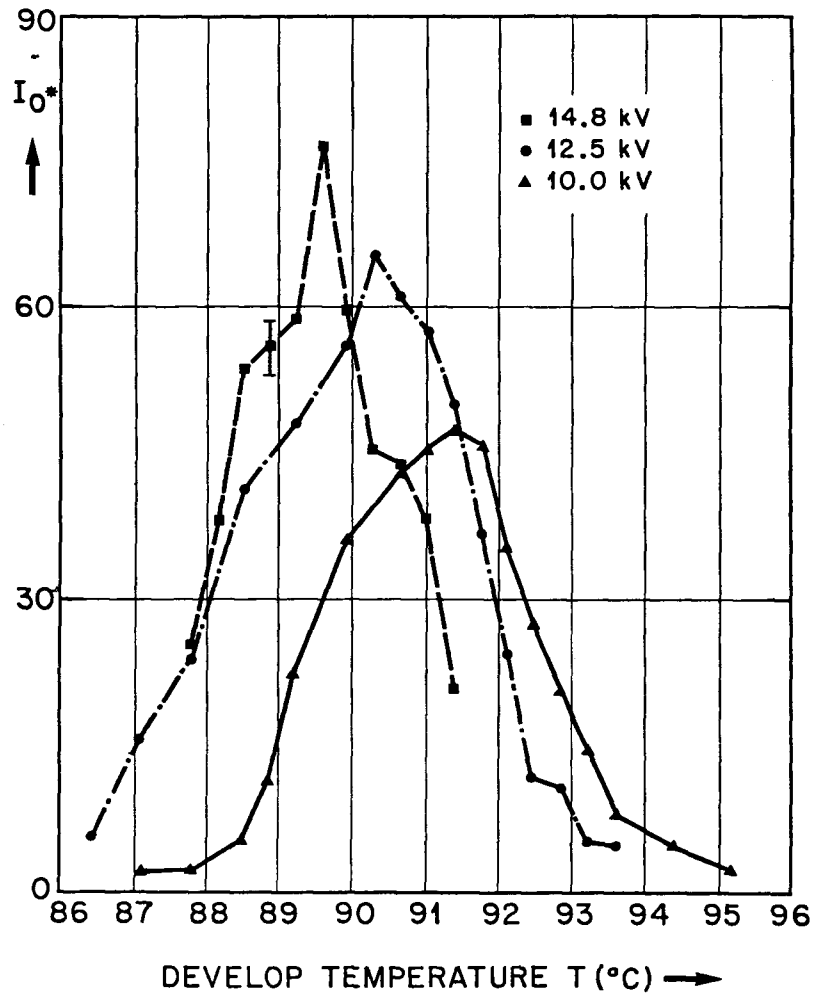


Fig. 4 Experimental result showing the brightness in the reconstructed image versus develop temperature for different corona voltages  $V_c$

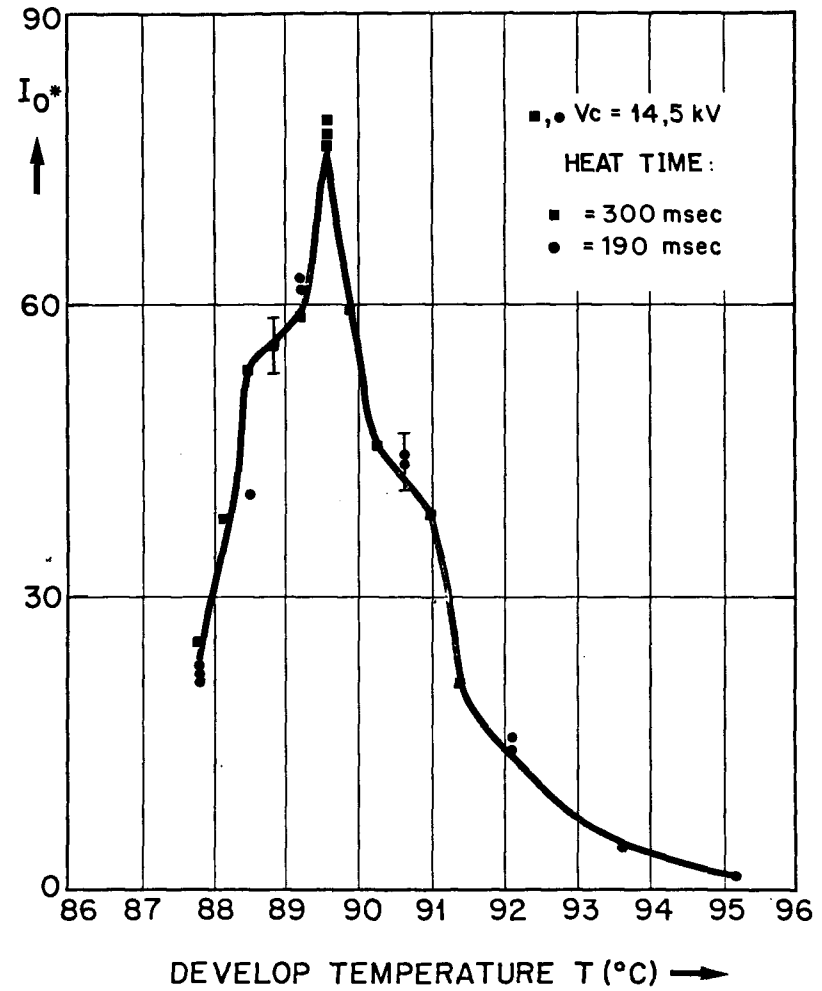


Fig. 5 Representative curve for develop temperature and different heating times

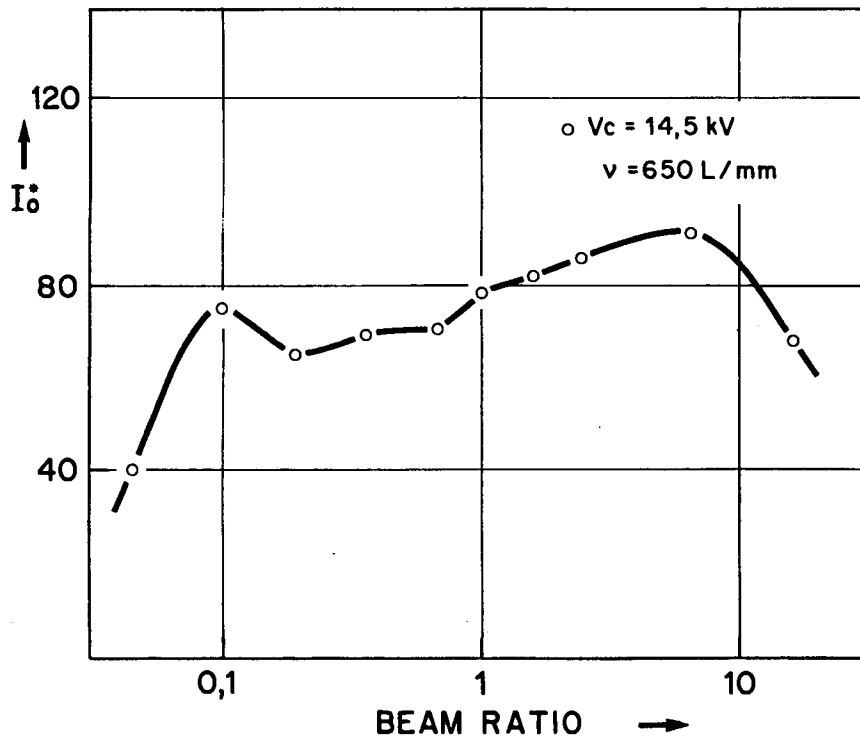


Fig. 6 Brightness in the reconstructed image vs reference-to-signal beam ratio

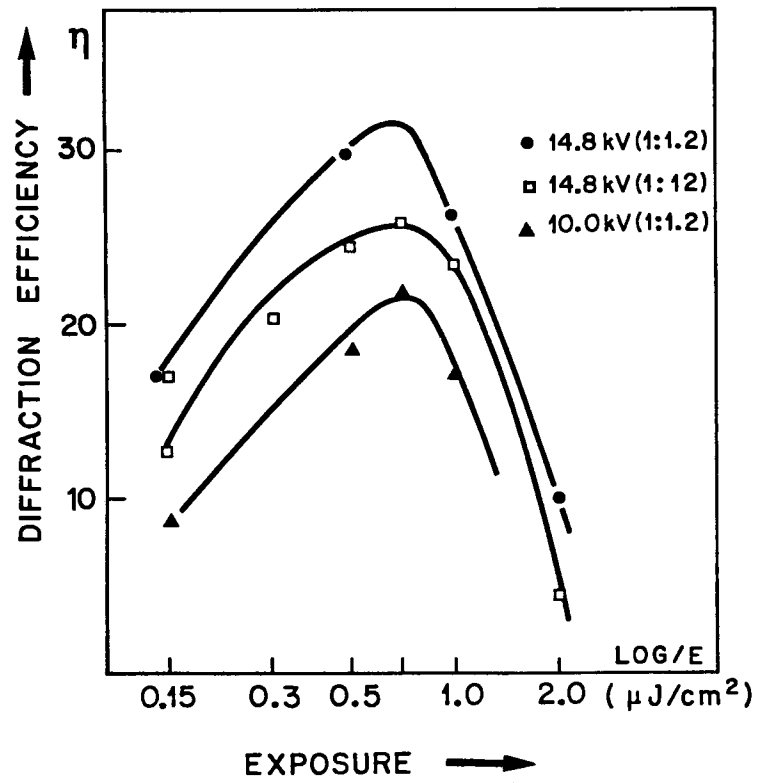


Fig. 7 Graph showing the dependence of diffraction efficiency on exposure

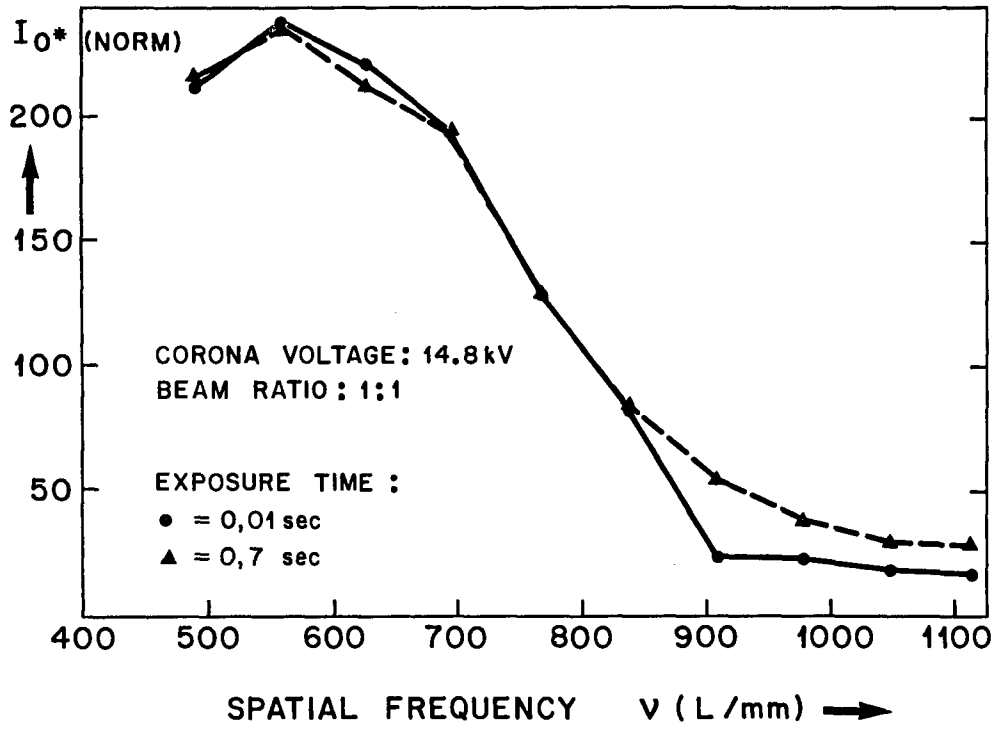


Fig. 8 Dependence of brightness in the reconstructed image on spatial frequency with different exposure times