A SYSTEM OF RECORDING DIGITAL DATA ON
PHOTOGRAPHIC FILM USING SUPERIMPOSED
GRATING PATTERNS

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The most common method for storing data in a binary form on photographic films has been to record each bit in terms of the presence or absence of a density in an area on the film. While in theory high-resolution materials have the inherent capacity for recording a tremendous number of bits within a given area, to a very great extent this has not been realizable because of technological difficulties. First of all, as the areas corresponding to the bits on the film are made smaller, they become more and more difficult to locate mechanically. And second, any film is bound to pick up a certain amount of dirt, and such particles can easily obscure individual bits and cause real havoc if high accuracy is required.

The method to be described represents a new system for recording such information, which largely circumvents both these difficulties and hopefully makes data recording on film a much more practical sort of operation.

The basic principle of this system is to record a bit of information as a small grating pattern on the film. As shown in Fig. 1, when such a pattern is placed in a simple optical system and the slit is illuminated with monochromatic light, two first-order lines will be formed. We can now place photodetectors at these lines and determine whether the grating pattern is in the aperture or not. It is interesting and important to note that the diffraction lines do not move when the grating pattern is moved.

So far we still do not have a very efficient recording method, but we can make it much more so by recording each bit in a given character as a pattern of a given spatial frequency and superposing the grating exposures on top of one another. Thus, for a character consisting of seven bits, we will now record a composite grating pattern consisting of up to seven spatial-frequency components. Figure 2 shows an enlarged composite grating consisting of seven components. The components are sinusoidal—or nearly so—in this case.

When such a pattern is placed into our optical system, a pair of first-order lines will be present in the focal plane for each component frequency of the composite pattern, as shown in Fig. 3. We can therefore place a photodetector at the position of each first-order component, on one of the sides at

Figure 1. Optical system producing zero-order and first-order lines from a simple grating.
least, and determine whether a spatial frequency has been recorded or not.

Figure 4 shows diagramatically the position we would want for the first-order lines. On the basis of simple grating theory you can show that the distance between a given first-order component and the zero-order image will be directly proportional to the spatial frequency, which means that, for an even spacing of the lines, we want to have equal increments between the spatial-frequency values. Likewise, because there is a possibility that a second-order line will be formed, all the spatial frequencies should be contained within a single octave.

Figure 5 shows a series of actual photographs of diffraction patterns formed from various composite grating patterns. It is obvious that the lines are very distinct and that an unambiguous signal is formed.

The practical limit for the number of spatial frequencies within a given area appears to be about seven or eight since the line intensities drop off rather rapidly as the number is increased beyond this point. But with seven frequency components it is not uncommon to find that the stronger of the first orders have intensities of about 5% or even as high as 10% of the zero order.

It should be pointed out that if the information of seven bits spread uniformly over the area otherwise occupied by the seven density areas in the conventional system, this system should be less sensitive to dirt and scratches because the area for a given bit is at least seven times as large. For the same reason, the problem of mechanically locating an area is much less difficult. This system is similar to the basic approach to holography. In fact, it turns out that a composite grating is essentially a Fraunhofer-type hologram of a series of bright points.
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While these patterns can be made very small, there is a limit to their size; this is illustrated in Fig. 6. Suppose that the composite grating is in the aperture plane of the optical system. There will then be a distribution of light at the zero order which is a diffraction pattern whose size, \( w_0 \), will vary inversely with \( L \), the size of the aperture, as shown by the equation at the left. The equation on the right, obtained from grating theory, gives the distance between the centers of two adjacent first-order lines. Since for well-formed gratings, the first-order components will have the same width distributions as for the zero order, we can define a redundancy factor \( R \) as the ratio of \( W_1 \) to \( W_0 \). When \( R \) is equal to unity the two adjacent first-order lines will be just at the limit of resolution and \( W_1 \) will be equal to \( W_0 \). This would occur, for example, if the pattern dimension were 1/10 mm and the spatial frequency increment were 10 cycles/mm. Thus by increasing either \( L \) or \( \Delta \nu \), we are able to increase the resolution of the lines. Practical experience as well as calculations have shown that obstructions such as dirt particles can cause difficulties for small values of \( R \), but as it is increased to five or more, the probability of false readings is greatly diminished.

To give just a little more insight as to how this system works, suppose that a set of seven spatial frequencies ranging from 70 to 130 cycles/mm was recorded as shown in Fig. 7. The basic interval between spatial frequencies would again be 10 cycles/mm. As has been pointed out, for a redundancy of unity the pattern would have to be 1/10 mm or 100\( \mu \) long. Suppose now that these same bits are recorded using clear and opaque areas in this same dimension of 100\( \mu \), as shown in the lower part of Fig. 7. Then it would be necessary to have a resolution of at least 7 lines per 100\( \mu \) or 70 lines/mm, which is of the same general magnitude as is required by the diffraction system.

To increase redundancy with the conventional system, the clear and opaque areas would be made larger, which is essentially throwing away the resolution available in the system. In the diffraction system, the resolution is used when the pattern is enlarged. Many fine-grained films have a capability of resolving many times what has been required for most conventional film data-storage systems, but with the new system we have means for putting it to use.

One method of forming very good composite images is with the use of variable-area composite patterns of the type shown in Fig. 8. These can be photographed with a camera system using a cylindrical lens in front of the objective lens so that the image illuminance is made to vary as the composite function.

From the collection of the Computer History Museum (www.computerhistory.org)
spatial frequencies in the lower one have been phased to give a minimum overall amplitude while this was not done in the upper one. The width as a function of distance is given in each case by the equation below the patterns.

It can be seen that the first term in each of these is the constant $b$ which represents a "bias" or average light level that is necessary to prevent the function from becoming negative. In the situation shown at the bottom of the figure, the bias level can be reduced to less than one-half of that shown at the top. To a first-order approximation, the intensity of the diffracted light that is monitored increases as the square of modulation of the component spatial frequency, and this would mean that it would increase as the square of the reciprocal of the bias level—that is, as $(1/b)^2$. Therefore, one should be able to increase the light approximately by a factor of four by properly phasing the patterns and reducing the bias level.

A method more adaptable for recording grating patterns is illustrated in Fig. 9. In this system, as the spot sweeps across the face of the cathode-ray tube, the intensity is modulated by any combination of the seven oscillators shown schematically in the figure. The temporal frequency of the oscillator, of course, will control the spatial frequency of the pattern as it appears on the cathode-ray tube. Each oscillator then controls one bit of information in a given character and a composite pattern can be made on the tube face by summing up the outputs of the oscillators.

The patterns are then photographed onto the film as it moves in a film transport. The height of the patterns can be controlled by placing a cylindrical lens in front of the tube face to image the line into the aperture of the lens. By orienting this cylindrical lens so that its refraction is perpendicular to the direction of scan line, the whole lens will appear uniformly bright at the objective lens. The cylinder can then be masked to the desired dimension.

One distinct advantage of this type of read-in system is that, since the patterns are superimposed as electrical signals, the bias can be adjusted to any desired value. Experience has shown that the strength of the first-order diffraction patterns can be increased considerably by first obtaining proper phasing of the patterns to reduce the overall amplitude of the composite signal itself while not reducing the amplitudes of the individual components, and then reducing the bias level to as low a value as possible, as was shown with the variable area patterns. In fact, a certain amount can be gained by reducing the bias to the point where a considerable amount of clipping takes place at the low intensity portion of the image.

With this sort of apparatus, it has been possible to record at a rate of about 15,000 patterns per second. The dimensions of each of the patterns were 500 by 7. The long dimension was in the direction perpendicular to the lines. Up to seven spatial frequencies ranging from 70 to 130 cycles/mm with a 10-cycle/mm increment were recorded in a pattern area. Thus the redundancy factor was equal to 5—that is, 10 cycles/mm times 500 μ.

With pattern dimensions of 500 by 7 microns and with the characters separated by 7 μ, the packing density is about $6 \times 10^5$ bits/in².

The narrow dimension of the pattern is essentially limited by the resolution of the system, and excellent diffraction patterns can still be obtained from very narrow grating patterns. However, increasing this dimension does serve to increase the system redundancy.

A second type of recording technique is illustrated in Fig. 10. With this arrangement of prisms, individual grating patterns are illuminated from separately controlled sources, only one of which is...
shown, and are imaged onto moving film with a single high-quality lens. Composite gratings can be produced through sequential addition of the individual gratings by gating the light sources in synchronism with film motion. However, memory and logic devices are required to maintain proper relations between coded inputs and photographic characters.

With emulsions having modulation transfer function characteristics similar to those of Recordak Micro-File AHU Film, Type 7459, the number of elemental gratings (binary ones) is practically limited to seven per photographic character. However, to allow a sufficient number of bits for timing and error correction in addition to those required for digital information, it is desirable to provide as many as ten bits per character. This is readily accomplished by means of a dual-track format in which each track contains up to five bits.

Of several possible light sources, the Sylvania Modulated Light Source SC4079P-11 has been found best suited to the present application. It consists essentially of a simple, high-current electron gun with electrostatic focusing but without deflection electrodes. The phosphor is coated on a metal face plate positioned at 45° to the tube axis. By collecting radiation from the face of the phosphor on which electrons impinge, a considerable increase in radiant output over a conventional CRT is obtained. Radiation patterns show that in a direction normal to the tube axis the intensity is about half that in a direction normal to the face plate. For this reason the tube axis was generally oriented at 45° to the position shown in Fig. 10.

In other respects the light source exhibits the same characteristics as conventional CRT's and a compromise must be made between photographic speed and the grating quality that can be obtained with available optical elements. Phosphor persistence is such that modulation rates in excess of 100 kc are reasonable. However, the variation of effective spot diameter with grid modulation places a more severe restriction on recording rates. At low and moderate levels of brightness the spot diameter is relatively small so that only the central zone of the objective lens is illuminated. Image quality is excellent but recording rates are low. As the brightness is increased for higher speeds, the spot diameter also increases, and the outer zones of the lens, which are prone to spherical aberration, are illuminated. The problem was minimized by using a 10-mm microscope objective operating at about f/1.2 and by restricting spatial frequencies to the 50–90 lines/mm octave. In this frequency range and at a magnification of 30:1, adequate exposure on Micro-File AHU Film, Type 7459, was obtained at character rates up to 60 kc.

A system for reading out small pattern areas such as these is shown schematically in Fig. 11. This system makes use of a high-pressure mercury arc. While the level of the diffracted light is rather low, it is sufficient to operate photomultiplier tubes. A cylindrical lens can be used beyond the film to reduce the first-order lines into small spots of light. As noted, an important feature of this type of reading out is that the position of the diffraction lines does not move when the grating pattern moves. This greatly simplifies tracking since with a 500 micron long grating for example, lateral movement of the record by as much as 25 microns or one mil can be tolerated without significantly affecting the signal strength. The motion simply effectively shortens the grating.

A much higher light intensity can be obtained by using a helium neon laser as a light source, as shown in Fig. 12. In this case the diffracted light intensity can be used to operate photodiodes without difficulty at frequencies approaching 100 kc.

While it will take considerably more work to make systems of this type that are operationally foolproof, experience has indicated that the principles of operation are sound and that by using this type of system, much of the high-storage potential of fine-grained photographic materials can eventually be realized.
Figure 11. Readout optical system for illuminating a small area of the film. The nearly monochromatic green line of a high-pressure mercury lamp is imaged onto the slit at the left, which, in turn, is imaged by both lenses in succession. The mask is imaged by the second lens onto the film and serves to limit the illuminated area.

BIBLIOGRAPHY


Figure 12. Read-out optical system with a helium-neon laser for illumination. A mask for controlling the width of the illuminated area can be placed at the second cylindrical lens. The height of this area can be controlled by the \( f \)-number of the objective lens and its focus.