Nonlinear-optical processing by means of phase coding

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A new look at nonlinear-optical processing that uses Fourier plane filtering is discussed. Traditional binary intensity-to-space recording (halftoning) is replaced by simple continuous phase coding. Some proof-of-principle experimental results demonstrate a superior 10^3:1 input dynamic range. The phase response of the photosensitive material can be measured as an addition to this proposed technique.

Although nonlinear-optical processing with halftones is still an attractive goal for researchers,[1] there are two major obstacles blocking the way of practical implementation of this technique. First, since the halftone process involves intensity-to-space coding, a specially designed halftone screen is required. The transmittance profile of each cell of the halftone screen has to be adjusted to compensate in advance for some recording medium effects, namely, that the medium is not a binary recorder. Moreover, a halftone screen cell shape must be calculated according to the type of transformation to be performed.[2] The realization of all varieties of halftone screen can be performed only on high-resolution plotting microdensitometers or digital image recorders (scanners).

Second, real-time implementation of the nonlinear transformation with halftoning requires the use of an optically addressed spatial light modulator, which may not be a binary recording medium and may have a limited input dynamic range (perhaps just 1 order of magnitude).

However, it is possible to look at the problem of nonlinear-optical transformation with halftones from another prospective. It is well known that any diffraction order selected in the Fourier plane of the conventional two-lens ($2f$) coherent optical processor[3] contains the full input image information. This is a consequence of the modulation of the input image by a periodic structure whose spatial frequency is higher than the maximum image spatial frequency. (In fact, some losses in resolution of the transformed image are always assumed.) However, this simple modulation does not lead to image transformation through filtering in the Fourier plane. In addition, we need to encode the input gray levels of the image by the intensity of the spectral components or, in other words, map input gray levels to a distribution on a Fourier plane.

The above-mentioned halftone process can be described by the following one-dimensional analysis. After hard-clipping recording, we obtain a set of rectangular transmittance gratings having the same period T but with a duty cycle ratio q varying as a function of input intensity I_{in} according to $q = q(I_{\text{in}})$. If the local transmittance of the portion of the halftoned image is

$$t(x) = 1 - \sum_{n=-\infty}^{\infty} \text{rect}\left(\frac{x - nT}{qT}\right), \tag{1}$$

where a certain duty cycle ratio appears as a result of the corresponding input intensity I_{in}, then the intensity distribution in the Fourier plane is expressed by

$$T(\nu) = F\{t(x)\} = \delta(\nu) - \sum_{n=-\infty}^{\infty} \delta\left(\nu - \frac{n}{T}\right) Tq\,\text{sinc}(\nu Tq), \tag{2}$$

where $\delta(\nu)$ denotes a delta function.

Thus, if the nth diffraction order is selected, the transformation rule from I_{in} to output intensity I_{out} is

$$I_{\text{out}} = \frac{T^2}{\pi^2 n^2} \sin^2[\pi n q(I_{\text{in}})]. \tag{3}$$

Here, the variable q is determined by the recording material's characteristic curve and a halftone screen transmittance profile.

Taking this as a starting point, one may think of a type of coding for which the local input intensity affects another grating parameter, such as amplitude. Evidently a simple linear recording on transmittance-function-type material (silver halide negative film) does not produce a nonlinear, nonmonotonic transformation. However, the intensity in a given diffraction order of the grating recorded on a material with phase modulation will behave nonmonotonically and will depend on the amplitude

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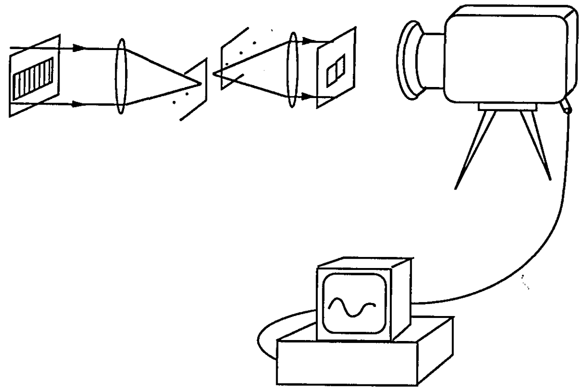

Fig. 1. Coherent optical image-processing system.

of phase modulation and thus is a function of the input image's gray level.

We now present a technique for nonlinear processing with phase coding and discuss the experimental feasibility of this approach, which uses dichromated gelatin (DCG), photoresist, and erasable photopolymers. The nonlinear, nonmonotonic nature of the phase recording becomes clear from the expression for the one-dimensional transmission function for a purely phase sinusoidal grating:

$$t(x) = \exp\left[jA \sin\left(2\pi \frac{x}{T}\right)\right], \tag{4}$$

where A is an amplitude of modulation.

When the well-known expansion

$$\exp\left[jA \sin\left(2\pi \frac{x}{T}\right)\right] = \sum_{n=-\infty}^{\infty} J_n(A) \exp\left(j2\pi n \frac{x}{T}\right) \tag{5}$$

is used, it follows that the intensity of an nth selected Fourier component of a diffraction spectrum is proportional to $J_n^2(A)$, where $J_n(A)$ is an nth-order Bessel function of the first kind. This means that

$$I_{\text{out}} \sim J_n^2[A(I_{\text{in}})], \tag{6}$$

since the recorded modulation is a function of the input intensity. This method has some advantages over conventional halftoning. In particular, the zero diffraction order, which generally has the highest diffraction efficiency, has nonmonotonic behavior. Also, the coherent processor with a phase transparency input is more light efficient than with a halftoned input image, and the high diffraction orders area is easily observable. Moreover, we do not have a strong restriction on the grating period since we can use a simple grating instead of designing a special screen.

Note that expression (6) is an approximate description of diffraction from a phase grating, valid only for so-called thin gratings.[4] A rigorous theory has been developed for planar phase gratings with an optical index modulation[5] and for phase gratings with surface relief modulation.[6] Some results of this theory are used to explain our experiment.

The traditional 2-f coherent optical processor setup is shown in Fig. 1, and the output intensity profile is measured by a charge-coupled-device video camera connected to a PC-based image-acquisition system. Any horizontal line of the intensity profile can be displayed and measured. This system was examined with a specially prepared mask, which serves to simulate a halftoned image. The mask has many gratings with the same period but with duty cycle ratios that vary linearly from 0.03 to 0.97. The observed transfer functions (Fig. 2) agree with the predictions based on Eq. (3). The estimated mean-square error is less than 10%. The measured intensity fluctuations are due mainly to the ground glass placed in the observation plane.

In the phase coding experiment, two types of photosensitive material were used: DCG and photoresist. When a sinusoidal grating (T = 50 μm) is copied onto the DCG film, the optical index modulation inside the film is a prevailing factor. The object was simulated by a continuous neutral-density filter with optical-density D changes from almost 0 to 3.0. After a standard development procedure, the plate was placed at the entrance of the processor. An example of the transfer function for the selected first diffraction order is shown in Fig. 3. The transformation dynamic range of 3 orders of magnitude was observed. This is a significant improvement over previously achieved results.

To compare the result with a predicted transfer function, we first note that for the film thickness d = 15 μm and grating period T = 50 μm in the experiment, the grating is definitely thin, based on the Q criterion[4]

$$Q \equiv \frac{\pi^2 d^2}{T^2} \frac{(\Delta n)^2}{n^2} < \frac{\pi^2}{8}, \tag{7}$$

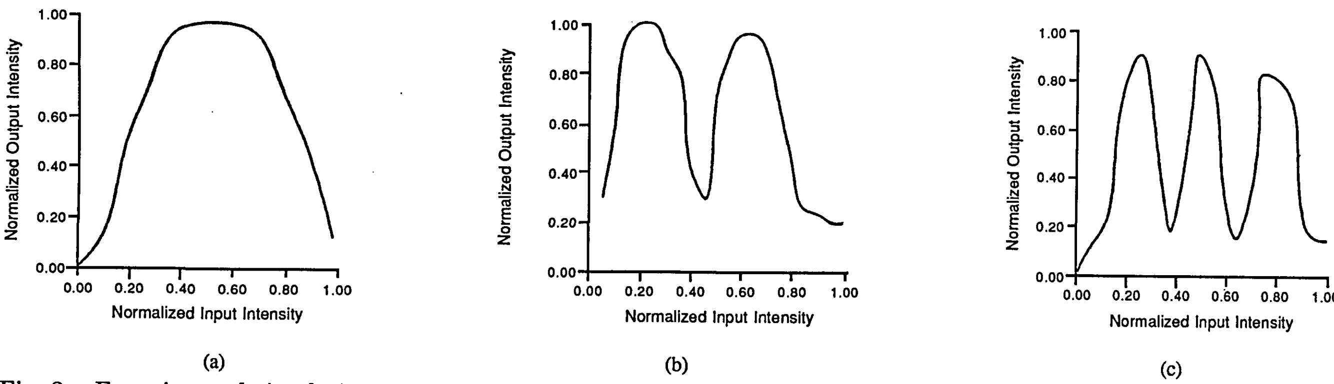

Fig. 2. Experimental simulation of nonlinear-optical processing. An example of nonmonotonic transformation for the (a) first, (b) second, and (c) third orders.

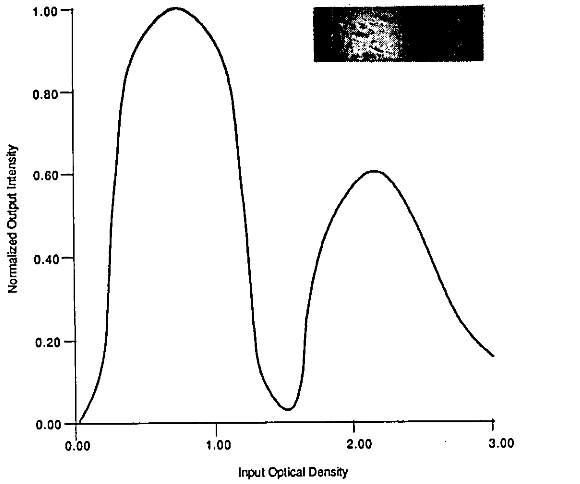

Fig. 3. Example of nonmonotonic transformation achieved with phase coding. The first diffraction order is selected.

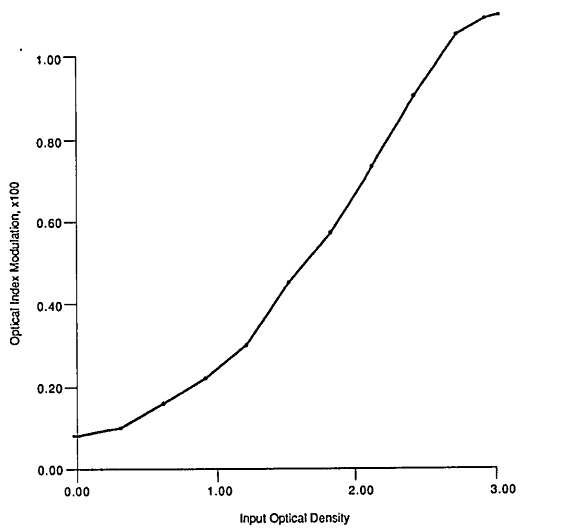

Fig. 4. Characteristic curve of DCG photopolymer derived from transformation data in Fig. 3.

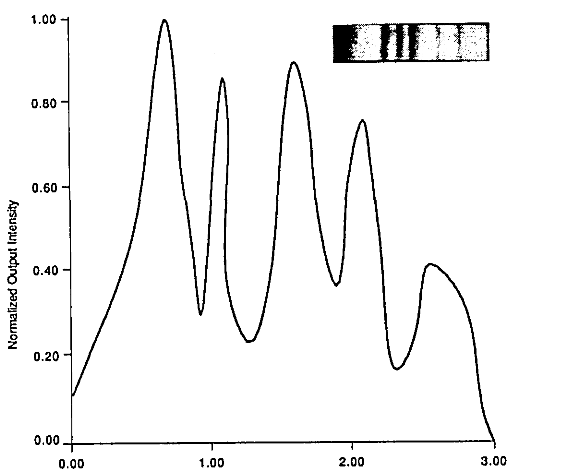

Fig. 5. Multipeak transfer function of optical processor with photoresist as a phase-recording material.

when $n = 1.51$ is used as an average optical index of DCG and $\Delta n = 0.01$ is the optical index modulation. Thus the first diffraction order should obey the Bessel function rule

$$I_{out} = CJ_1^2\left[\frac{\pi\Delta n(D)}{n\lambda}d\right], \tag{8}$$

where $\Delta n(D)$ is a characteristic curve of DCG.

Choosing the constant C to normalize the experimental curve so that $J_{max}^{exp} = J_{1\,max}$, we can compute the characteristic curve of DCG. The result, as shown in Fig. 4, closely approximates what is known about DCG. Other diffraction orders also behaved nonmonotonically, as expected.

Another phase-recording material to be employed for phase coding is photoresist, which forms primarily a surface relief. This type of grating cannot be considered a thin grating, and its diffraction efficiency as a function of groove depth is described by the rigorous coupled-wave theory. The resulting diffraction efficiency as a function of groove depth is more like a sine-squared form. We examined photoresist as a recording material for a nonlinear processor by copying a Ronchi-type grating on it, forming a square-wave surface relief grating. The transfer function for this case is shown in Fig. 5. Although the dynamic range is narrower than that of DCG, the maximum achievable modulation is higher. Thus several peaks occur in the transfer function that are useful for equidensitometry.

The proposed method also permits a real-time implemenation. It can be performed by using either a purely phase spatial light modulator or an erasable photopolymer material.

The proposed method has potential applications in optical information processing. With this in mind, other phase-recording materials such as dry processing photopolymers (Dupont photopolymer) and plastic polymers with extremely high phase modulation are worthy of future investigation.

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