

## Design and Fabrication of Highly Efficient Fan-Out Elements

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This paper reports the calculation and fabrication of periodic phase structures for fan-out elements with a theoretical conversion efficiency close to 100% and perfect uniformity. We have measured an efficiency of 92% for a smooth kinoform structure fabricated in photoresist by laser beam writing lithography.

**KEYWORDS:** fan-out, kinoform, phase grating, Dammann grating, CGH, HOE

Optical fan-out elements split a single laser beam into a one- or two-dimensional array of beams. Fan-out elements are key components in many applications of modern optics, such as parallel optical processing and fiber optic communication. Similar elements can also be used for beam shaping of laser diode arrays.<sup>1)</sup> Binary phase gratings, also called Dammann gratings,<sup>2)</sup> represent a successful technique to fabricate fan-out elements with good uniformity of the generated array of beams, but moderate efficiency (60%–70%). More recently, efforts are concentrated on kinoforms in order to increase the diffraction efficiency. This paper deals with the calculation and fabrication of smooth periodic phase structures as fan-out elements with a theoretical conversion efficiency (single-beam/multi-beam) close to 100%. In addition, the presented design method requires only low computing power, even for very large fan-outs.

A fan-out element can be considered as far-field hologram of a one- or two-dimensional array of coherent light sources (Fig. 1). The light sources of the array, spaced by the distance  $s$ , are characterized by their amplitudes and phases,  $A_i$  and  $\phi_i$ . For a linear array of  $N$  point sources on the  $x$ -axis we can write the near-field amplitude distribution  $U(x, y)$  as

$$U(x, y) = \sum_{m=1}^N A_m \exp [i\phi_m] \delta(x - x_m, y), \quad (1)$$

with  $x_{m+1} - x_m = s$ .

The far-field distribution  $\hat{U}(u, v)$  is related to the near field  $U(x, y)$  by a Fourier transformation. Thus, we get for the far-field

$$\begin{aligned} \hat{U}(u, v) &= \sum_{m=1}^N A_m \exp [i\phi_m] \exp [2\pi i x_m u] \\ &= |\hat{U}(u, v)| \exp [i\Psi(u, v)], \end{aligned} \quad (2)$$

where  $\Psi(u, v) = \arg \{ \hat{U} \}$ . In the far-field intensity distribution we can observe interference patterns with periodicities of  $1/s, 1/2s, \dots$ , described by<sup>1)</sup>

$$I(u, v) = |\hat{U}|^2 = \sum_{m=1}^N A_m^2 + 2 \sum_{k=1}^{N-1} B_k \cos [2\pi k s u + \Phi_k]. \quad (3)$$

For a given set  $A_i, \phi_i$ , the intermodulation terms  $B_k$  can be calculated by

$$\sum_k B_k \cos [2\pi k s u + \Phi_k]$$

$$= \sum_{n < m} A_m A_n \cos [2\pi u(m-n)s + (\phi_m - \phi_n)], \quad (4)$$

where  $k = m - n$  and  $n < m = 1 \dots N$ .

The corresponding hologram, considered as a phase grating with  $\Psi(u, v)$  of eq. (2), becomes only efficient, if these intermodulation terms are minimized, otherwise part of the input energy is diffracted into undesired beams. Minimum power of the intermodulation in eq. (3) means that

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left( \sum_k B_k \cos [2\pi k s u + \Phi_k] \right)^2 du dv \rightarrow \min. \quad (5)$$

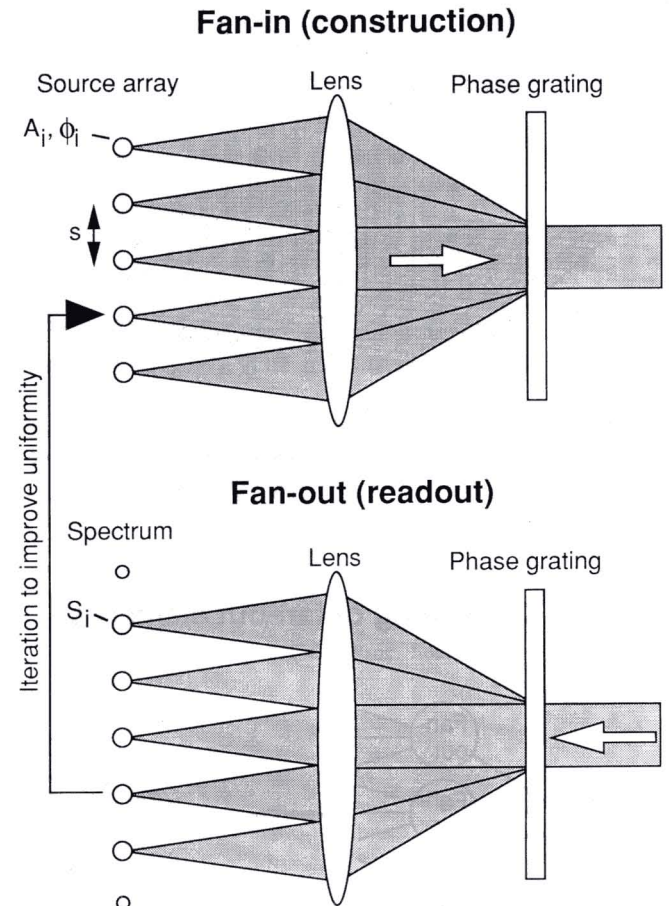


Fig. 1. Construction and read-out of fan-out elements.

As the terms with different spatial frequencies are orthogonal, the minimum condition becomes finally

$$\sum_k B_k^2 \rightarrow \min. \quad (6)$$

This can be achieved by appropriate choice of the phases  $\phi_i$ , obtained by numerical optimization.<sup>1)</sup>

This consideration is independent of the technology used to fabricate the phase element, it holds as well for surface relief elements (kinofoms) as for volume holograms. The fan-out corresponds to the spectrum of the phase grating (Fig. 1). In general, the amplitudes  $S_i$  in the (calculated) spectrum will be different from the initial  $A_i$ . However, by iteration the uniformity can be improved.

Figure 2 shows the spectrum of an optimized smooth phase grating for a linear fan-out element which generates  $N=9$  beams of equal intensity. The conversion efficiency is 99.3% and the uniformity is perfect. To calculate the optimum fan-out element, we start with the amplitudes  $A_i=1$  and optimize the efficiency by varying the phases  $\phi_i$ . Then, the spectrum of the corresponding phase grating is calculated, yielding the amplitudes  $S_i$  generated in the readout (Fig. 1). In general, they are different from the desired values for a uniform fan-out, which is  $S_i=1$  for  $i=1 \cdots N$ . By iteration, i.e. by increas-

ing or decreasing the amplitude  $A_i$  if the corresponding  $S_i$  is smaller or larger than 1, a perfect solution is found after a few steps. Efficiencies close to 100% can be achieved for nearly any fan-out with  $N>6$ .

Large fan-out elements with high efficiency can be constructed with negligible computing time by cascading the solutions found for smaller fan-out elements as shown in Fig. 3. For example, we can start with an optimized fan-out element generating a linear array ( $N=9$ ) characterized by the parameters  $A_i$  and  $\phi_i$  (Fig. 1). By cascading, we get a much larger array with  $N=9^2=81$ , characterized now by  $A_k=A_i A_j$  and  $\phi_k=\phi_i+\phi_j$  with  $i, j=1 \cdots N$ . This method can be generalized by multiple cascading and by combining arrays of different sizes. In general, the resulting elements will still have a very high efficiency (close to 100%), however, the uniformity of the fan-out becomes bad, so that additional iteration is necessary to restore it.

Figure 4 shows the spectrum of an optimized phase structure for a 2-dimensional fan-out element, which generates  $9 \times 9$  beams of equal intensity. The conversion efficiency is 99.3% and the uniformity is perfect. This element has been calculated by crossing two linear fan-out elements. Crossing means cascading two linear arrays which are perpendicular to each other, in order to generate a 2-dimensional array. As is described above, the characteristic parameters are then given by  $A_k=A_i A_j$  and  $\phi_k=\phi_i+\phi_j$  with  $i, j=1 \cdots N$ . Crossing has the advantage that the uniformity of the fan-out is conserved, because the two dimensions are independent.

After all, for this type of fan-out elements the fabrication becomes the limiting factor for the efficiency and the uniformity. A very promising approach is to fabricate the phase structure by laser beam writing lithography as smooth relief grating in photoresist. We used the design of a fan-out element, which is highly efficient (99.3%) but not completely uniform ( $\pm 5\%$  theoretically), to fabricate a corresponding kinoform in collaboration with the PSI/RCA Laboratories.<sup>3)</sup> The profile of the developed photoresist relief shown in Fig. 5 has been measured mechanically. The grating period is  $\Lambda = 500 \mu\text{m}$

**Fan-out 9x1 : amplitude distribution**

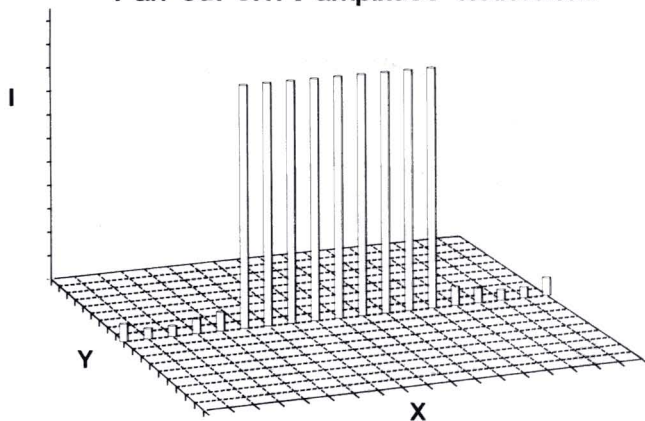


Fig. 2. Spectrum of an optimized smooth phase grating for a linear fan-out element, which generates 9 beams of equal intensity. The conversion efficiency is 99.3% and the uniformity is perfect.

**Cascading of fan-out elements**

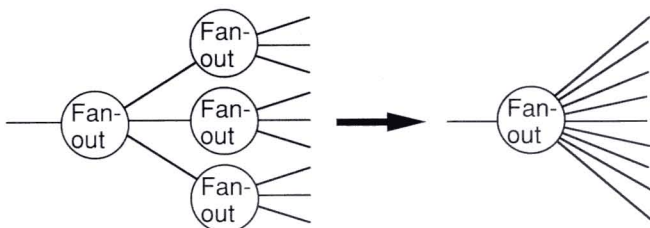


Fig. 3. Cascading of fan-out elements.

**Fan-out 9x9 : amplitude distribution**

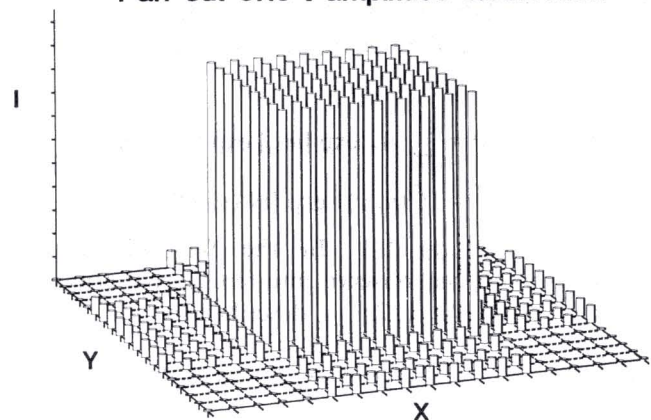


Fig. 4. Spectrum of an optimized phase grating for a 2-dimensional fan-out element, which generates  $9 \times 9$  beams of equal intensity. The conversion efficiency is 99.3% and the uniformity is perfect.

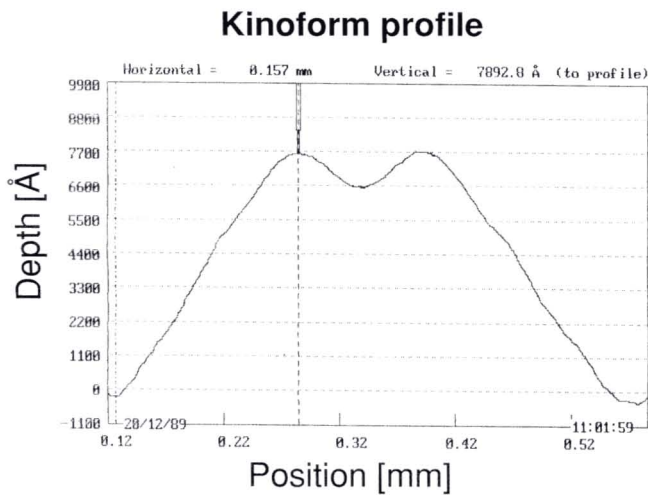


Fig. 5. Profile of the smooth relief grating in photoresist, fabricated in collaboration with the PSI/RCA Laboratories by laser beam writing lithography.<sup>3)</sup>

and the measured depth of  $0.77 \mu\text{m}$  corresponds well to the desired value. The photoresist relief structure can be converted into a metal master relief by electroplating techniques for mass-production of low-cost replicas.

To test the fan-out, we have illuminated the phase grating described above (Fig. 5) with a plane wave from an argon laser ( $\lambda=488 \text{ nm}$ ). The smooth kinoform element generates 9 fan-out beams (Fig. 6) containing 92% of the total light power transmitted through the element. We have measured intensity variations of  $\pm 7\%$ . The corresponding spots have been detected with a CCD camera. For comparison, the theoretical and the experimental values for the relative intensities of the fan-out beams are given. The theoretical results for the design described in Fig. 5 are 99.3% for the efficiency and  $\pm 5\%$  for the uniformity.

Another method to fabricate fan-out elements uses a computer-generated hologram (CGH) to produce an array of coherent sources with optimized phases for minimum intermodulation, which can be used to record efficient holographic optical elements (HOE) as volume phase gratings in dichromated gelatine or photopolymer. This holographic recording technique allows also to include focussing power into the fan-out element. A similar phase structure as shown in Fig. 5, with a period of  $\Lambda=96 \mu\text{m}$ , has been encoded as CGH and then fabricated by electron beam lithography at the CSEM.<sup>4)</sup> The carrier frequency of the CGH is  $\nu=250 \text{ lines/mm}$ , sufficient to separate the different diffraction orders. Illuminated with a laser beam at  $\lambda=488 \text{ nm}$ , the first

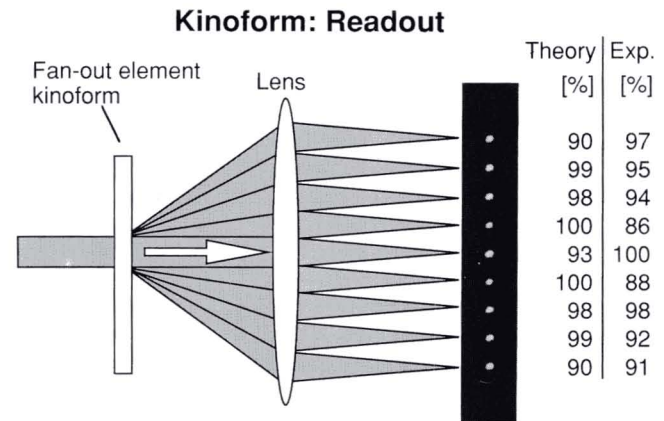


Fig. 6. Spectrum of the smooth fan-out element (Fig. 5) at  $\lambda=488 \text{ nm}$ . The experimental results yield an efficiency of 92% (99.3% theoretical) and intensity variations of  $\pm 7\%$  ( $\pm 5\%$  theoretical).

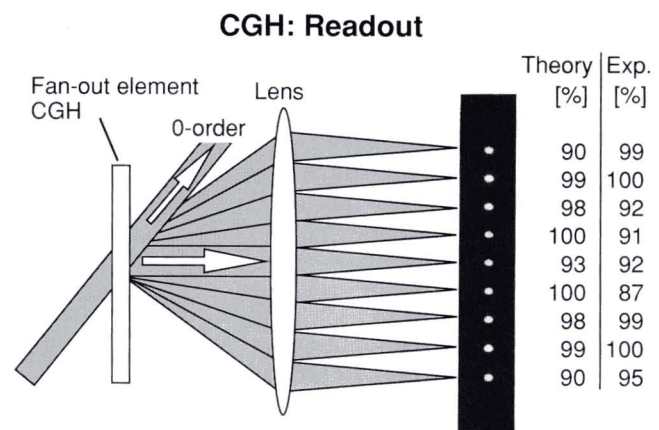


Fig. 7. Spectrum of the CGH fan-out at  $\lambda=488 \text{ nm}$ . The measured uniformity is within  $\pm 7\%$ . The CGH has been fabricated by electron beam lithography at the CSEM.<sup>4)</sup>

diffraction order of the CGH generates the desired array of sources (Fig. 7). The measured uniformity is within  $\pm 7\%$ .

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