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Asymmetric Three-Beam Binary Optic Grating

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Abstract

Binary and diffractive optical components are finding many applications in optical systems and integrated optical devices. A recent application required the development of a two-dimensional diffraction grating to perform an asymmetric, three-beam fanout. In this paper, techniques are presented for the design of arbitrary fanout grating devices. Modeling and optimization processes are demonstrate for the three-beam grating. The counter-intuitive results of the initial design are discussed, and experimental data verifying performance is presented.

Introduction

The growth in fabrication techniques using lasers and optical signal processing has produced a significant opportunity for innovation and the development of new optical devices.[1] Specialized gratings, designed to redirect light into specific diffraction orders, are finding many applications in optical interconnects, signal switching and interferometry. As the complexity of the fanout increases, particularly if the desired orders are asymmetric, the conventional design process becomes untenable and a non-deterministic optimization algorithm must be utilized.

A fanout device has been designed which produces three diffracted beams with equal power in each diffracted order, (see figure 1). The grating operates in transmission under normal incidence, directing light into three non-planar orders. The triangular geometry requires suppression of symmetric orders, increasing the mathematical complexity of the design effort. An attempt was made to design the grating in a deterministic manner using standard scalar diffraction theory, but yielded no solution. To overcome the limitations of our initial approach, a simulated annealing algorithm was used to produce a solution.

Approach

The fanout device produces three diffraction orders with equal power in each diffracted beam. The triangular geometry requires suppression of symmetric orders, which increases the mathematical complexity of the design effort. An analytic solution was attempted, but yielded no solution. The calculations did reveal that, due to the low angular deviation of the three beams, a scalar simulation code would provide accurate solutions, provided features in the grating structure were kept relatively large.

A simulated annealing algorithm was developed using a scalar simulation code to predict grating performance. A grating unit cell was defined as a 64 x 64 two-dimensional array of discrete phase values, thus the dimension of the problem was n = 4096. The irradiance in the central diffraction orders was calculated by coherent summation of the information in the discretely sampled unit cell. Irradiance targets were set to 0.33 for the 0,1, -1,-1 and 1,-1 orders with the remaining orders set to 0. The unit cell was initialized with random phase values prior to application of the annealing algorithm. During optimization, the convergence parameter or "cooling temperature" was decremented as a harmonic sequence. The cost function for the annealing algorithm was based upon the mean squared error between the simulated irradiance values and the target values. Figure 2 outlines the logic flow for the simulated annealing algorithm. Designs were attempted with two, four, and eight discrete phase levels permitted in the grating. We found that the algorithm converges to the three desired orders very rapidly. Balancing the power in the orders, however, required a much greater fraction of the optimization time. The algorithm converged well for grating patterns of four or more phase levels; the asymmetric output required was not achievable using a binary phase grating. The results for the four level grating was counter-intuitive, but showed a simple repeated pattern (see figure 3).

Since the optimization was performed on an isosceles spot array, (orders 0,1, -1,-1 and 1,-1), a mapping was required to form the desired equilateral pattern. This was achieved by a linear scaling in x direction by a factor of 0.894. The scaled pattern, shown in figure 4, is the baseline design for the fanout device.

Evaluation of the pattern showed that it consists of two repeated shapes. The first is a hexagon with top and bottom sides concave, and the second is a bi-convex "football" shape. Each unit cell consists of four hexagons, each of a different phase level, and four footballs, also with different phase levels. The grating is constructed of these unit cells tiled into a tightly packed array.

The triangular output pattern suggests that shapes within the unit cell have edges at angles of 0°, 60° and 120°. In an effort to improve diffraction efficiency, the football shapes were replaced with small hexagons of similar shape and equal area. A simulation of this grating pattern demonstrated higher diffraction efficiency, but also a shift in the uniformity of the three beams. The size of the small hexagons was adjusted until irradiance in the beams was balanced. The result of this post optimization yielded an increase in diffraction efficiency from 77% to 79%, and only a slight change in the beam uniformity of less than 4% deviation. A signal to noise (SNR) value was calculated by comparing the irradiance in the weakest of the three beams to the irradiance in the highest undesired order present. The post optimization provided a boost in SNR from 8.4 to 11.2.

A second benefit of the modifications to the baseline design was a simplification in the mask patterns required to produce the optic. The two mask patterns required to produce the four level device were designed on Teledyne Brown Engineering's Computer-Generated Holography Workstation and are shown in figure 5. The patterns were written as a reticle at 5x and a step and repeat camera was used to create the masks. The fanout grating was fabricated in the binary optics processing lab at Teledyne Brown.

Test Results

Preliminary laboratory results have been completed on the three-beam fanout grating. To provide a simple measure of performance, the total laser power is measured and compared to the three diffracted beams. Figure 6 is a graphic depicting the percent power diffracted into each of the desired beams. A measure is also provided of the zero-order power. The undiffracted light provides a measure of processing errors encountered in the fabrication.

Analysis of the masks used to create the grating revealed dimensional inaccuracies resulting from processing errors. Sources of the errors involved the mask fabrication and subsequent replication. To better control etch depth and alignment across the large grating, (85 x 85 mm), a self masking technique was used. This procedure involves the use of a metal coating which must be chemically etched. Most of the dimensional errors have been traced to the photoresist exposure and the metal removal process used in the self masking procedure. The dimensional errors created difficulty in aligning the second mask to the first, resulting in errors of up to 0.5 microns. We are fabricating a second optic without this technique to assess the impact of self masking. This second three-beam grating, fabricated to better tolerances, will be subjected to more complete testing.

Conclusions

Optical fanout gratings of increasing sophistication are required for many current applications. As the complexity of the element increases the conventional design process becomes untenable and a non-deterministic optimization algorithm must be utilized. We have demonstrated a design approach using a simulated annealing algorithm to produce a baseline grating structure. This baseline can then be reviewed and further optimized by the system designer. Our initial design has been fabricated and experimental results demonstrate proof of principle.

Future work will include restructuring the merit function and the target values for the diffraction orders. We believe that this would allow the algorithm to converge more directly toward the solution designed during post optimization. Future work will also include the development and application of more advanced non-deterministic optimization algorithms, particularly genetic algorithms. Preliminary data suggests that as the dimension and complexity of the problem increase, genetic algorithms may achieve a global solution with reasonable rapid convergence.

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References

1. Alan Kathman and Eric Johnson,"Binary Optics: New Diffractive Elements for the Designer's Tool Kit". *Photonics Spectra*, pp. 125-132, September 1992.

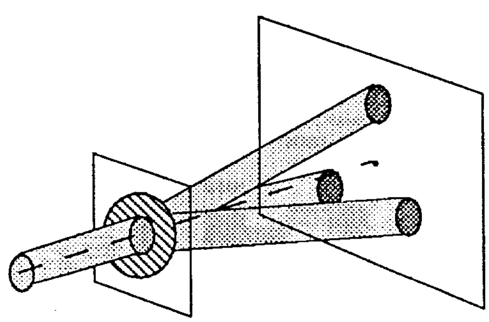
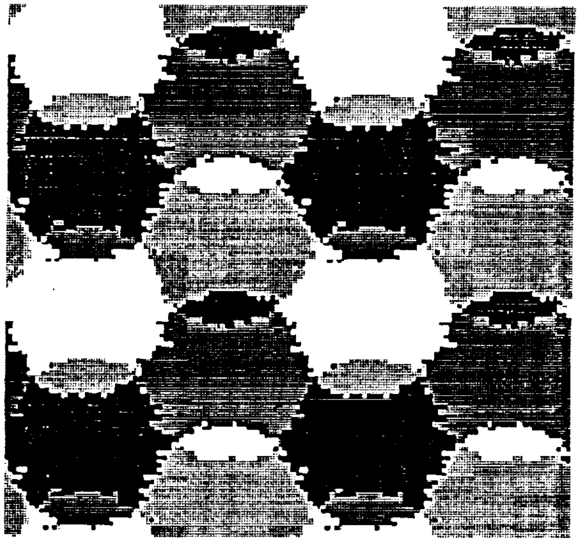
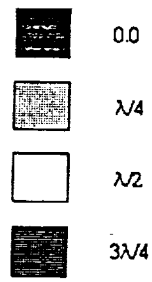


Figure 1. Functional performance of an asymmetric three-beam fanout grating.

```
Random Initialization;
Tinitial = 1.0;
t = Tinitial;
f1 = cost();
For ( i=0; i<MAX; i++) {
    perturb();
    f2 = cost();
    residue = f2 - f1;
    if ( residue < 0 ) {
        update();
        f1 = f2;
    } else {
        boltzman = exp(-residue/t);
        rnum = random(0., 1.);
        if ( rnum < boltzman ) {
            update();
            f1 = f2;
        }
    }
    t = Tinitial / (1 + i );
}
```

Figure 2. Simulated Annealing algorithm for fanout grating optimization.





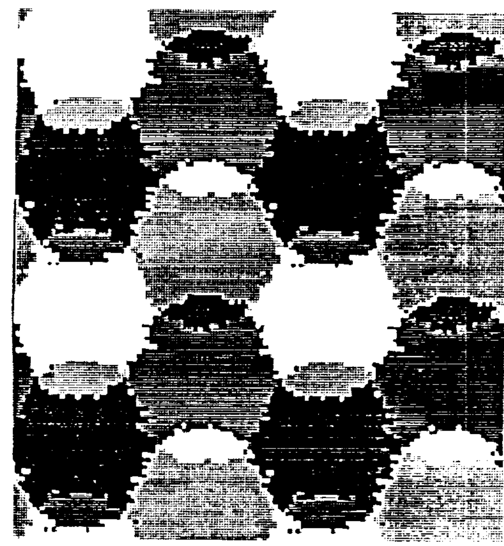


Figure 3. Four phase level pattern produced by simulated annealing.

Figure 4. Scaled pattern necessary to produce equilateral triangle.

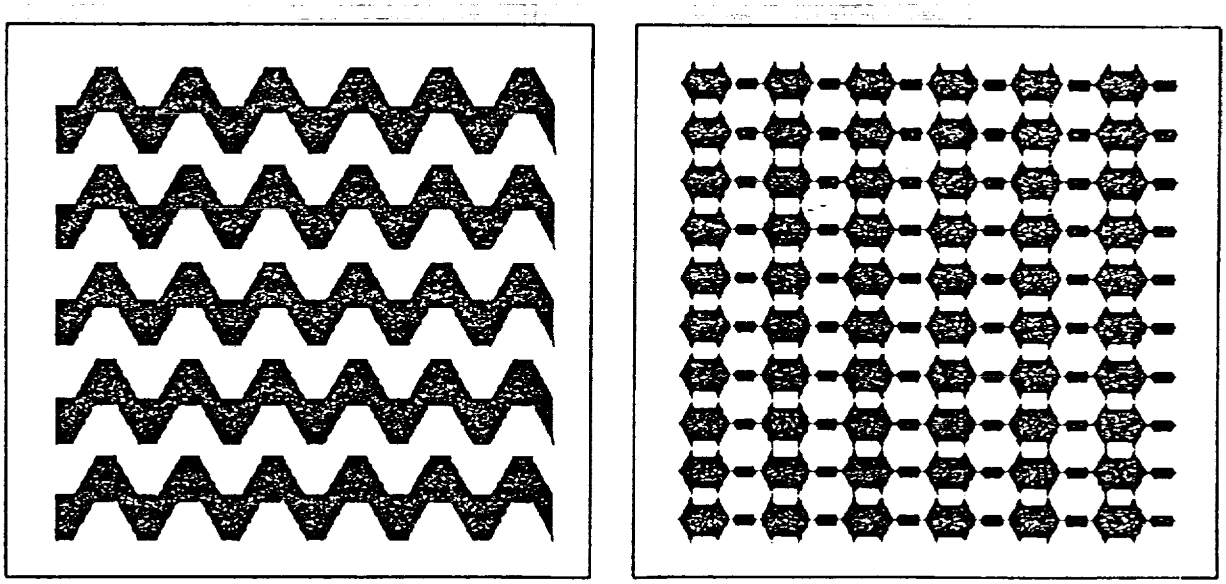


Figure 5. First and second layer mask reticles for three-beam grating fabrication.

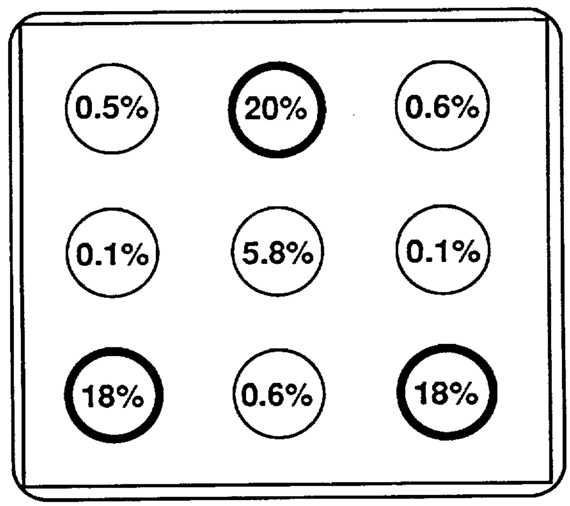


Figure 6. Preliminary experimental results showing the percentage of diffracted light in the nine lowest orders.