The Fabrication of 2D Multilevel Phase Holographic Beamsplitters
Using E-Beam Lithography
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The results of 2D multiple-levels phase holographic high efficiency laser beam-splitters computer design and fabrication using direct E-beam phase relief recording in E-resist layer, chemical and reactive ion etching processing are described. The good agreement between theory predictions and the performance of fabricated splitters for a visible range of waves is observed.

Introduction

As well known, the synthesis of diffractional optical elements (DOE) with given power distribution in far diffraction zone has no exact solution. The methods developed by us and realized as the application package, of computer synthesis of two-dimensional (2D) multiple-levels phase holographic laser beam-splitters allow to design splitters with power efficiency greater than 70% and power error less than 3% [1]-[3].

We also have investigated the technological process of direct E-beam multiple-levels phase relief recording in an E-resist layer including E-beam exposing, chemical development and controlled reactive ion etching processing [4].

The developed techniques were successfully applied to experimental fabrication of 2D laser beam-splitters for visible range of light waves.

Computer synthesis of holographic beam-splitters

In an approximation of scalar theory of diffraction and supposing the diffraction element aperture to be rather great (at least some periods of complex transmittance function on each dimension), it is possible to perform discret Fourier analysis of a single period of DOE complex transmittance function instead of continuous Fourier analysis of the total DOE aperture while accounting for the diffraction far zone distribution (output distribution). Our computer synthesis of DOE is fully based on paraxial Fourier optics and is carried out for single period of phase function 64x64 pixelled structure in four design steps [3].

At the first design step we use iterative methods of obtaining continuous output phase distribution and corresponding continuous either quantized DOE phase function starting with randomized output phase distribution. The fixed number of iteration cycles is fulfilled saving the best intermediate result.

At the second design step we optimize the continuous output phase distribution to obtain the best corresponding continuous either quantized DOE phase function.

The optimized quantizing of continuous DOE phase function by adjusting phase discrimination levels is fulfilled during iteration either phase optimizing process.

At the third design step we optimize the quantized DOE phase function by switching quantized values of a single or several pixels simultaneously. The most critical pixels on different-phases areas boundaries are varied first of all for the sake of acceleration of the optimizing process.

At the fourth design step the topological phase relief optimizing is carried out by minimizing the number of different-phases areas, smoothing different-phases areas boundaries and minimizing the total length of these boundaries to minimize fabrication errors and to improve the power efficiency.

Two phase levels are sufficient for centrally symmetrical output power distributions while at least three phase levels are needed in other case.

Holographic multiple-phase elements fabrication technology

The traditional multiple-levels surface-relief phase elements fabrication technology assumes a number of cycles of laser-beam or E-beam lithography and reactive ion or plasm burning etching of a surface for creation phase delay levels. We are describing here basic results of investigations of direct E-beam multiple-levels phase relief recording in E-resist layer including E-beam exposing, chemical development and controlled reactive ion etching processing [4].
The maximum phase relief depth is limited by thickness of a resist layer on glass substrate. The exact depth of a phase relief is obtained by combination of chemical development and reactive ion etching processing of an exposed structure with periodic monitoring of output power distribution.

The fabrication of the multiple-levels phase element was carried out as follows.

On a glass substrate surface using centrifuge was supposed the E-resist layer. The E-resist layer drying was carried out by IR-heating during 30 min at 100°C temperature. Then the sample was heated for a short time up to 150°C for E-resist layer melting and surface smoothing.

On E-resist surface using vacuum thermal evaporation using installation "L-560Q LEYBOLD-HERAEUS" was placed thin (0.015 µm) conducting layer of aluminum, serving for removal of static charge while E-beam exposing.

For electronic exposing the E-beam complex on the basis of a measuring scanning electronic microscope "ZRM-20 CARL ZEISS" and IBM PC/486 based image generator was used, ensuring a positioning accuracy 0.02 µm and an exposing accuracy 0.5%. The diameter of an electronic beam was adjusted within 0.01-0.05 µm range. Usually it takes about 3 hours of exposing time when aperture size is 5.5 x 5.5 mm².

After E-beam exposing the conducting layer of aluminum was removed by chemical etching.

**Fig.1. “3x4/2” splitter, 2 phase levels, 12 working diffraction orders of equal intensity. Even working diffraction orders number at one dimension and odd at another dimension, non-working zeroth diffraction order.**

The chemical development of E-resist was carried out using mix of i-propanol and metyletylketon. To select an optimum exposure value and an optimum development time the
dependence of resist etching depth versus exposure value and a development time was measured. The measurements were fulfilled by recording special phase test structure, with known dependence of the phase delay versus zeroth and first output diffraction orders powers ratio. Again this dependence was used later to determine current phase delay while photometric measurements.

The exact adjustment of the phase level values was fulfilled using reactive ion etching processing of the resist surface in soft and strictly controlled conditions on installation "XLP-200 HENNON". The sequential cycles of etching and spectro-interferometrical measurements of layer thickness were carried out to determine the reactive ion processing etching rate and its stability.

**Experimental results**

The described above techniques were applied to fabrication of various type phase holographic laser beam-splitters with different numbers of phase levels. The splitters were fabricated for working wave lengths 0.532 and 0.633 µm. The aperture of all splitters was 4.6x4.6 mm², phase function period size 230.4x230.4 µm², pixel size 3.6x3.6 µm² (with 64x64 pixel grid). The angles between adjacent diffraction orders were 7.9 ° for green light splitters (wave length 0.532 µm) and 9.4 ° for red light splitters (wave length 0.633 µm).

\[ A \]

\[ B \]

\[ C \]

**Fig.2. “3x11/2” splitter, 2 phase levels, 33 working diffraction orders of equal intensity. Odd number of working orders in both dimensions and working zeroth diffraction order.**
Fig. 3. “IONT/4” splitter, 4 phase levels, 43 working diffraction orders of equal intensity. Non-symmetrical output power distribution.

In a summary table below and on Fig.1-Fig.3 theoretically predicted and experimentally measured performances of some laser beam-splitters designed and fabricated by us are presented. The power efficiency was determined as ratio of the total working diffraction orders power and the total incident light power. The power error was determined as the maximum deviation of normalized output power distribution from the required one. The far diffraction zone power distribution (output distribution) was also controlled using CCD TV camera and computer image analysis. A good agreement between theoretically predicted and measured performance (efficiency and power error) is observed.

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Splitter Type</th>
<th>Phase Levels</th>
<th>Efficiency/Error (Theory)</th>
<th>Efficiency/Error (Experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>“3x4/2”</td>
<td>2</td>
<td>74.3% / 0.50%</td>
<td>70.3% / 5.4%</td>
</tr>
<tr>
<td>2</td>
<td>“3x11/2”</td>
<td>2</td>
<td>73.7% / 1.93%</td>
<td>71.3% / 4.5%</td>
</tr>
<tr>
<td>3</td>
<td>“IONT/4”</td>
<td>4</td>
<td>72.9% / 8.10%</td>
<td>69.1% / 9.5%</td>
</tr>
</tbody>
</table>

On Fig.1-Fig.3 A) different tones correspond to different phase values and B) spot area is proportional to diffraction order power.

On Fig.4 A) B) the SEM reflected electrons micrograph and optical interferometrical microphoto of the “3x11/2” binary-phase splitter phase relief surface are shown. The high quality of phase relief realization is observed. Separate pixels of 64x64 phase function period grid of size 3.6x3.6 µm² are visible. Imperfections of initially supposed and developed E-resist layer are much less than the pixel size.
On Fig. 4 C) - D) the tunnel probe electronic microscope image of a small fragment of the “3x11/2” binary-phase splitter phase relief surface and the corresponding phase relief profile are shown. The separate pixel of size 3.6x3.6 µm² is seen. The high quality of a phase relief realization is observed.

Summary

The methods developed by us of 2D multiple-levels phase holographic laser beam-splitters of computer synthesis allow to design splitters with arbitrary diffraction orders power distribution with efficiency greater than 70% and power error less than 3% [3]. The main features of our computer synthesis procedure are 1) taking the optimum but not the last DOE continuous output phase distribution obtained during a fixed number of iteration cycles carried out for multiple randomized initial output phase distributions, 2) DOE continuous output phase distribution optimizing using multiple-coordinates descending optimizing procedure, 3) DOE continuous phase function optimum quantizing using multiple-coordinates descending optimizing procedure, 4) DOE quantized phase function combinatorial optimizing using switching of quantized values of several boundary pixels simultaneously, 5) DOE quantized phase function topological optimizing by minimizing of the number of different-phases areas as well as the total length of boundaries between them.
The investigated by us methods of direct E-beam multiple-levels phase relief recording in an E-resist layer by using E-beam exposing, chemical development and controlled reactive ion etching processing of a surface relief allow to realize required DOE phase relief with high accuracy [4]. The developed technique allows to obtain any required number of phase levels of required values (also not equidistant when needed). Methods of direct E-beam multiple-levels phase relief recording were successfully applied to fabrication of 2D multiple-levels phase holographic laser beam-splitters for visible light wave range.

The good agreement between theoretically predicted and experimentally measured performance of various types splitters fabricated using developed techniques is obtained.

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References