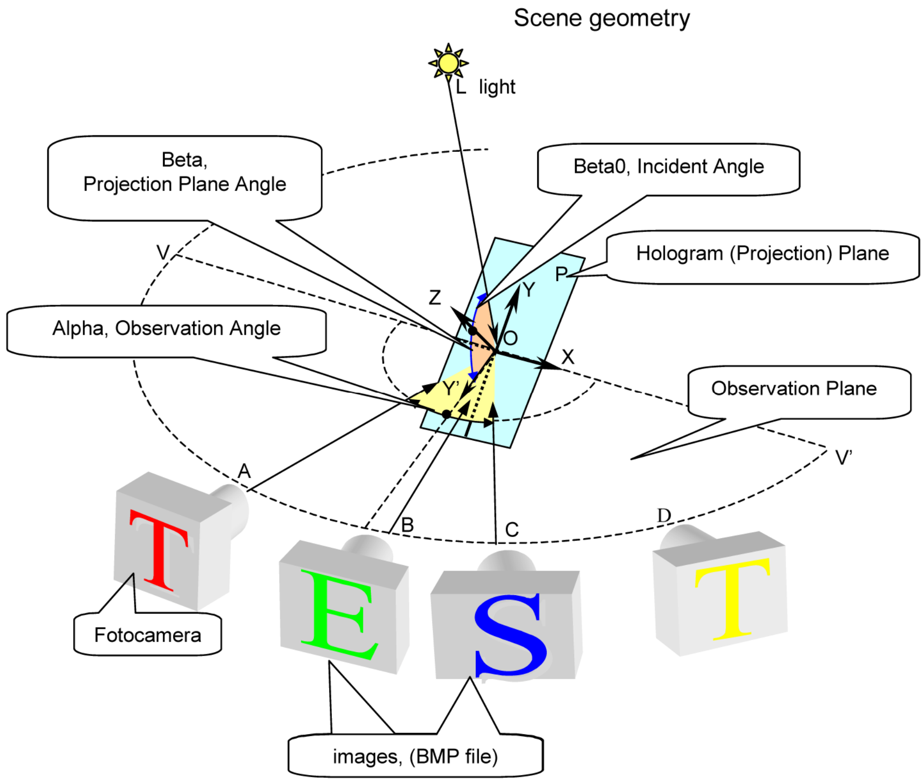

Fig. 12. Scene geometry of rainbow hologram projected from the observer viewpoint.

6. Discussion

Before comparing the proposed approach with the dot-matrix and existing e-beam techniques let us recall the main new features implemented in the new approach. The designing part realizes two methods for proper color synthesis what includes variations of a duty cycle and a grating size. To increase the hologram tolerance to random swinging during observing, a special controllable divergence is added to equalize the blur of all the three pixels used in color presentation. A remarkable feature of the design is flexibility in the pixel shape which now could not only be a square and a rectangle but even not a rectangle at all. The lithographic data is optimized by the considering EBL proximity effect that results in perfect reproduction of the gratings pitch and duty cycle and, as a consequence, in perfect color reproduction. Lithographic data describing a hologram, if stored in common data formats like GDSII, results in an enormous volume of information so a special format for hologram data presentation was developed enabling easy data transfer from a remote place of design to a computer controlling the lithograph. A very important simulation tool is provided which takes only geometry of gratings into consideration. The tool allows looking through and analyzing a future image, which enables optimization of a hologram before real fabrication.

6.1 Comparison with the dot-matrix approach

The history of the dot-matrix technique, the progress of increasing its quality and throughput are described in [19]. The principles and the newest dot-matrix setups including dot-image devices are described in [20]. This is now a mature and widely used technique [24–27].

The main advantage of electron lithography is its unprecedented resolution based on a small electron beam diameter. The resolution exceeds wave limits of optical (dot-matrix) devices of visible range by many thousand times [18]. Combined with a fine control system, the resolution provides high flexibility of writing strategies. Closely packed pixels could be arranged in arbitrary shapes including not only square and rectangular but also those similar to very complicated Escher cells [18].

However, electron lithography is a sequential technique whereas the dot-matrix approach operates in a parallel manner exposing the whole grating. In general, the time per master is a not critical point in the rainbow hologram fabrication and tens of hours per master is acceptable in a production line. Nevertheless, accurate consideration of the throughput of the two techniques show that a dot-matrix machine needs mechanical moving to expose the next pixel and this slows down the rate of writing. Estimates and practical experience showed that a square inch of a rainbow hologram can be produce by SEM-based electron lithography within ten hours which is practically equal to the production time with a dot-matrix device.

Electron lithography provides a higher quality of gratings as is shown by the comparison of the EBL gratings of Figs. 8 and 9 with the best dot-matrix gratings (see Fig. 11 from [20]). Note that Figs. 8 and 9 show 6um gratings whereas Fig. 11 from [20] contains 25um grating. Moreover, no cross-talking of gratings occurs in electron lithography.

As mentioned above the proposed approach includes the addition of blur for equalizing light divergences of R, G, B gratings, which is provided by the curvature of gratings (see Figs. 6, 8 and 9). Such equalizing in divergence is not possible in the dot-matrix technique because the interference scheme allows producing only straight fringes.

Color synthesis in the dot-matrix technique is not perfect in comparison to the approach described here. Two methods are used to control the intensity of R, G, B reflections in the dot-matrix machines: change of grating size and control of grating modulation [20]. The change of the grating size alone without divergence control and blur equalizing results in color error at hologram swinging as was shown above. As to the grating modulation control, this approach can be applied but it is very difficult to realize in practice. Resists which are usually used have a very high contrast and this leads to a very low tolerance of the production process to errors in the exposure dose, temperature, time of development, etc. The low tolerance was the reason why the grating modulation control was not even included as a standard function for color synthesis in the described approach although electron lithography uses 3D shaping for fabrication of kinoform diffractive optics and computer generated holograms [28, 6].

Dot-matrix technique can be simulated with RainBow software by eliminating controllable blur and using the gratings size change only at color synthesis. These simulations show that even a slight inclination (−2 degrees) result in very strong color error.

So one can consider grey-tone hologram as a new security element, which cannot be reproduced with dot-matrix techniques.

6.2 Comparison with industrial e-beam lithographs

Obviously, the main advantage of the proposed approach in comparison to electron lithography with industrial machines is cost reduction. Roughly the system based on the SEM column, EBL controlling system NanoMaker and special "RainBow" software is about ten times cheaper than the usage of industrial lithographic machines. But some topics should still be discussed in relation to the usage of industrial devices.

It is expected that the usage of such machine as lithographs with variable beam shape could decrease time of stamp fabrication but rainbow holograms are a particular case of the objects for which the technique of variable shape beam (VSB) cannot be applied in full measure. The fact is that the beam in the VBS machine has the shape of a rectangle (with size up to several microns), which cannot be rotated continuously. To realize the 2D/3D effect, stereo effect or kinematics effects, part of gratings should have a slight inclination (see Figs. 6 and 11). To realize such effects (by means of inclination providing) an operator of VBS machine should decrease the beam size to a minimum, which is equal to operating the machine in the mode of Gaussian beam. This reduces the writing speed making it equal to that of the SEM column. So, industrial lithographs have no significant advantages in the throughput of rainbow holograms in comparison with the usage of ordinary SEM column.

#222028 - $15.00 USD Received 2 Sep 2014; revised 9 Oct 2014; accepted 10 Oct 2014; published 11 Nov 2014

Additionally the industrial lithographs are equipped with laser stages to provide perfect stitching of nanometer scale over a size of several inches. Such a stage is not necessary for rainbow hologram production. A hologram consists of distinct gratings and the accuracy of several micrometers available for an ordinary mechanical stage is sufficient.

So, neither in throughput nor in accuracy industrial lithographs have not any advantages in comparison to the described approach based on the usage of on ordinary SEM column.

7. Conclusion

An approach for the fabrication of rainbow hologram designed with the “RainBow” software is presented. The approach is based on electron lithography performed with a SEM column and a special EBL controlling system NanoMaker. The approach of three basic color mixture is used to provide fabrication of full-color digital holograms. The designing tool (”RainBow”) uses the variation of a duty cycle of gratings and size of gratings for proper color synthesis. To increase the color picture tolerance at swinging, a method of equalizing angular divergence of each grating is developed and implemented. The approach allows one to fabricate gray-tone hologram (containing white color) what increases level of hologram security.

For EBL data preparation and optimization, a special design/simulation system “RainBow” was developed.

It is shown that the approach allows the fabrication of rainbow holograms of high quality with a higher tolerance to hologram swinging. The results of fabrication of large rainbow holograms from design to imprinting are presented.

The comparison with existing techniques such as dot-matrix and EBL with industrial lithographs clearly demonstrates the advantages of the described approach.