GENERATION OF SPATIAL LIGHT DISTRIBUTIONS

PhD theses

LÁSZLÓ DOMJÁN

TUTOR: DR. LÁSZLÓ KOCSÁNYI DOCENT

Department of Atomic Physics

Faculty of Natural Sciences

TU Budapest

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1. Introduction

A spatial light distribution can be characterised by the spatial distributions of the following physical parameters depending on the coherence properties of the light: field vector, intensity, mutual intensity, polarisation, spectral power density, radiance. As my scientific theses concern mainly practical applications I do not consider the different possibilities of mathematical interpretation of spatial light distributions with more details.

Different optical applications require the generation of spatial light distributions of different physical properties. E.g. a very general task of technical optics is the generation of a light spot with very small geometrical size that is applied in many fields as optical data storage, laser surgery, laser material processing, etc. The application of movie and image projection requires spatial modulation of the spectral intensity of light according to the image to be projected. Since in most of the cases the light emitted by the primary sources does not meet the requirements of the applications, hence additional optical elements are needed for the modification of the light radiation. Such an equipment consisting of one ore more primary light emitters and some optical elements for the modification of the properties of the emitted light can be called a *light source* or a *light modulator*. A spatial light distribution suiting to the requirement of a specific application can be obviously created on many different ways, which raises the problem of finding the technically and economically optimal solutions. Furthermore the steady development of technology enables to find more and more optimal solutions from time to time.

The first and second groups of theses are related to stripe illuminators for robotic applications, where the spatial modulation of the intensity and spectral intensity of light is required. The third groups of theses are related to spatial light modulation for holographic data storage applications, where the spatial modulation of the complex amplitude of polarised coherent light waves are considered.

2. Stripe illuminator based on LED array and parabolic mirror for active triangulation sensors used on mobile robots

Closely related publications: *1* and *2*

Description of the problem

The light sources illuminating only a stripe of space are called stripe illuminators. An ideal light-stripe is such a spatial light distribution in which the light intensity is constant inside a certain three dimensional stripe of space and zero outside of it. The most important application area of these light sources are the active triangulation sensors with structured illumination, which are also applied as obstacle recognition sensors of autonomous mobile robots (AMR). The target parameters of the developed stripe illuminator were specified according to the requirements of an obstacle recognition sensor developed for an experimental AMR of Siemens (ROAMER) and they are the following: 2m illumination range; stripe width of 6-8 cm; highest possible light intensity to detect objects with low reflexivity; high spectral intensity and simple capability of temporal modulation yielding high SNR against the background illumination in internal space; eye safety; simple construction for cheap production.

The construction and properties of the stripe illuminator

The above requirements can be fulfilled with a stripe illuminator constructed of a linear array of high power LEDs and a cylindrical parabolic mirror. The linear LED array is placed on the focal line cylindrical parabolic mirror and the LEDs are illuminating in the direction of the central line of the parabolic mirror. The light rays emerging from the LEDs are collimated in one direction by reflecting on the cylindrical parabolic mirror. An additional rectangular aperture placed at the plane of the LED array blocks the "off-axis" rays after reflecting on the mirror. This construction supplies very high total light power and intensity because of the large number of applied high power LEDs. The narrow bandwidth of the light emitted by the LEDs enables the spectral filtering of background illumination by applying an optical band-pass filter matched to the emission of the LEDs in the detecting optics. The application of cheap elements makes the stripe illuminator economically reasonable too.

I built a geometrical optical model of the selected high power LED (Siemens SFH487P, 880nm central wavelength) in an optical CAD system and designed a configuration (parabolic shape, distance between LEDs and mirror, size of rectangular aperture) optimally realising the above listed requirements. I made the tolerance analysis of the LED mounting that resulted tolerances of 0.2 mm for the positioning and 0.3° for the orientation.

The following simple and economic solution was found to realise the designed light source. The calculated parabolic shape was cut into thin metal plates by a precision laser material processing machine. More such metal plates were fixed side by side in a Al box and a flexible mirror foils was stretched onto the parabolic edges of the metal plates by springs. The accurate positioning and orientation of the LEDs were solved by a special assembling and holding frame.

The technical parameters of the realised stripe illuminator are the following. The stripe width is 75 mm (FWHM) at 2 m distance from the source. The intensity of the stripe are 5.5 mW/cm^2, 1.1 mW/cm^2, 0.6 mW/cm^2 at 0.1m, 1m and 2m distances respectively. The spectral intensity of the source was measured to be 69, 14 and 7.5 $\mu W/cm^2/nm$ at 0.1m, 1m and 2m distances respectively. Comparing these values with spectral intensities measured in internal spaces SNRs between 140 (room illuminated by artificial light) and 7 (room illuminated by strong sunshine) can be obtained depending on the intensity of the background illumination. The operation of the stripe illuminator was tested in a special active triangulation sensor. In internal space the light source supplied detectable signal even for objects of very small reflectivity, as black objects or objects made of transparent glass. According to the tests all types of objects except fully transparent or reflective surfaces of optical quality could be detected by the light source in internal space. By increasing the numerical aperture of the detecting optics and the detection time surfaces of optical quality may be also detected by the light source. The optical sensor was mounted onto an AMR to test the operation of the light source. The AMR could fulfil all of its navigation tasks by relying only on the signals of the optical sensor about the obstacles lying in its environment. I analysed the eye safety of the stripe illuminator based on physical principles and valid technical norms. Both analyses resulted that the stripe illuminator is eye safe.

Summary of new results in technical sciences

I. I recognised and justified with numerical calculations that the light source constructed of a cylindrical parabolic mirror, a linear LED array placed at the focal line of the mirror and a transmitting aperture of rectangular shape placed at the plane of the LED array realises a high power, eye safe stripe illuminator by which a stripe of less than 9 cm stripe width is illuminated within a distance range of 0-2m. I prove with test measurements that the intensity and spectral intensity of the light stripe are high enough even for the detection of objects with low reflectivity in internal space thus the stripe illuminator can be effectively applied in obstacle recognition sensors based on active optical triangulation. To reach the stripe width of 9 cm the LEDs should be positioned with 0.2 mm tolerance and the orientated with 0.3° tolerance, which are technically feasible requirements. These tolerance values were calculated in an optical CAD system based on a geometrical optical model of the LED.

II. I recognised that a technically and economically effective solution of this stripe illuminator is a flexible mirror foil stretched onto metal plates having the required parabolic shape; the accurate positioning of the LEDs can be solved with a special mounting and holding frame.

I prove with test measurements that the realised stripe illuminator supplied 75 mm stripe width (FWHM) within the 0-2 m distance range. As the light source of an optical triangulation sensor the stripe illuminator supplied signals high enough even for detecting objects with very low reflectivity (black objects, glass objects). The SNR against the background illumination varied between 140 and 7 depending on the intensity of background light. I justified with radiometric calculations and measurements prescribed by the valid standards that stripe illuminator is eye safe.

3. Theoretical and numerical examination of the stripe illuminator made of a linear emitter placed at the focal line of a cylindrical lens to optimise the operation in external space

Closely related publications: *3*

Description of the problem

These theses consider the generation of such spatial light distributions that allow active triangulation sensors to operate in external space. The most important noise source for the external operation of these sensors is the intense background light caused by sunshine. The most important condition of efficient operation in external space is that spectral intensity of the stripe illumination should be high enough compared to the spectral intensity of terrestrial solar illumination, consequently the spatial modulation of spectral intensity is required.

Examination of the stripe illuminator made of a linear emitter placed at the focal line of a cylindrical lens regarding operation in external space

I examined in which way stripe illuminators supplying high enough SNRs against solar illumination can be realised by the construction of a cylindrical lens and a linear emitter (in reality rectangular, but one edge is much shorter than the other one) placed at the focal line of the lens. This construction is very effective for realising high power stripe illumination because of the large surface size of the rectangular emitter. Such a light source can be constructed of many different emitter types as LED array, laser diode array and incandescent source, each of them have different physical sizes and angular emission characteristics. My main aim was to set up a general theoretical model by which the illumination of the different practical stripe illuminators can be described, their external space operation can be optimised and the different practical configurations can be compared. Firstly I built a radiometric model of the optical system assuming a spatially invariant rectangular emitter of arbitrary angular radiation distribution and an ideal cylindrical lens. The model resulted an integral by which the (spectral) intensity can be calculated in any point of the illuminated stripe. I determined the optimal focal length and numerical aperture of the cylindrical lens that couples the maximal light power into a stripe of given width from a rectangular emitter of a given geometrical size. By the numerical evaluation of the radiometric integral I examined the SNRs against solar illumination applying different practical rectangular emitters as linear LED chip array, linear array of packaged LEDs, laser diode array and tungsten incandescent sources. Stripe illuminators with four different geometrical parameters (see Table) were examined by the emitter types listed above.

Configuration	Illuminating distance	Stripe width
1	1 m	0.01 m
2	1 m	0.05 m
3	2 m	0.01 m
4	2 m	0.05 m

The SNR was defined as ratio of the spectral intensity of the stripe at maximal distance and the spectral intensity of direct solar radiation. The terrestrial solar spectrum published by the American Society for Testing and Materials were applied in the calculations.

By applying a linear emitter made of linear LED chip array SNRs over one were obtained with chips emitting at 450nm, 660nm and 950nm central wavelengths for all the configurations of the table. The 880nm LED chip array supplied SNR over one for the configurations 1,2 and 4. By applying a linear array of 950nm packaged LEDs SNRs over one were obtained for all the configurations except the 3rd one. SNR over one was obtained also by applying 660nm packaged LEDs for configuration 2. By applying a linear array of 5mW packaged laser diodes SNRs over 0.7 were obtained for all configurations at all the investigated wavelengths (405, 635, 785, 840, 950 and 1550nm). The 405 and 950nm laser diodes supplied SNRs over one for all the configurations. By increasing the power of the laser diodes the SNRs can be further increased. The SNRs were calculated also for tungsten linear sources of 2500K and 3000K temperatures. SNR over one were obtained for the 2nd configuration of the table at wavelengths over 800nm with the 2500K tungsten source and over 540nm with the 3000K one. These sources can be effectively applied if a stripe illuminator with very high total power and broad spectral band is required. For the configurations 1,3,4 the SNR was over one only in very narrow spectral bands (in the solar minima), thus the application of these sources is not advantageous because of the low power efficiency.

Summary of new results in technical sciences

I. I examined and modelled the stripe illuminator made of an ideal cylindrical lens and a spatially invariant rectangular emitter of arbitrary angular radiation distribution placed at the focal line of the lens to examine its effectiveness in external space measurements. I established a radiometric integral by which the (spectral) intensity of the illuminated stripe can be calculated for rectangular emitters of arbitrary angular radiation distribution and an ideal cylindrical lens of arbitrary focal length and aperture size. This model is able to describe practical stripe illuminators realised with different rectangular sources as LED array, laser diode array and incandescent source.

II. I defined the SNR as the ratio of the spectral intensities of the stripe illuminator and of direct sunshine. By the numerical evaluation of the radiometric integral I calculated the obtainable SNRs for stripe illuminators applying LED chip arrays, arrays of packaged LEDs and laser diode arrays operating at various wavelengths; I also calculated the SNRs using 2500K and 3000K tungsten rectangular sources. According to the obtained SNRs I selected those emitter types by which SNRs over one could be obtained: LED chip arrays of 470, 525, 660, 880, 940 and 950nm wavelengths; packaged LED arrays of 660 and 950 nm wavelengths (very simple and economical solutions!); array of packaged 5mW laser diodes of 405, 635, 785, 840, 950, 1050nm wavelengths; 2500K and 3000K tungsten incandescent sources in different spectral bands defined by the geometry of the illuminated stripe. By these calculations I showed that the stripe illuminator based on a cylindrical lens and a linear emitter can be effectively applied in external space measurements.

4. Ternary phase-amplitude (+1,-1,0) modulation with transmission type twisted nematic liquid crystal displays for smoothing of spatial intensity distribution of Fourier holograms

Closely related publications: *4* and *5*
Other related publications: *6-12*

Description of the problem

These theses concern with the spatial modulation of the complex amplitude of linearly polarised coherent light for holographic data storage. In Fourier holographic data storage data images of several bytes of information are stored in holograms. The data images are usually created by spatial light modulators (SLM), the Fourier transformation is made by an objective. A basic problem of Fourier holography is that intensity of the zero spatial frequency component can be several magnitudes higher than the average intensity of other frequencies. Storing such a hologram does not optimally utilise the dynamic range of the storing material. A well known method to destruct the zero frequency component is to give random phase modulations to the different SLM pixels. The conventional solution for this method is that the SLM is imaged onto a random phase mask with same pixel number and geometry as the SLM by an objective of sub-pixel distortion. Both the design and fabrication of an objective with sub-pixel distortion and the 6 axes alignment required for the pixel matched positioning of the SLM and phase mask are complicated technical tasks, thus this is a very uneconomical solution. Furthermore for those data images in which the bright SLM pixels well correlate with the phase mask pixels of similar phase shifts the zero frequency component is not destructed, thus they should be prevented by coding techniques that leads to data capacity losses. Because of the above described reasons it would be very advantageous to realise the spatial amplitude and phase modulation of light required for the generation of Fourier holograms with smoothed intensity distributions with a single SLM pixel.

Realisation of ternary phase-amplitude (+1,-1,0) modulation with transmission type twisted nematic liquid crystal displays

My research work concerned with the problem of realising the required complex amplitude modulation of light by applying a single pixel of a transmissive twisted nematic LCD. The simplest answer for the described problem is the ternary phase-amplitude (TPA) modulation containing three states with complex amplitude modulations of +1,-1 and 0. This modulation scheme is already known in the field of correlation filters.

The complex amplitude modulation of an ideal transmission type twisted nematic LC cell can be described by a Jones matrix assuming that the LC molecules are uniformly twisting within the LC medium. According to the model the LC cell has two important parameters: the phase retardation that can be modulated between a maximal value and zero by applying electrical field to the cell, the maximal value is taken at zero field; and the twist angle of the LC molecules within the cell that is invariant to the applied electrical field and approximately equal to ±90° for commercially available LCDs. The elements of Jones matrix are non-linear functions of the phase retardation and the twist angle. In order to obtain TPA modulation I placed the LC cell between an "elliptical polariser" and an "elliptical analyser"[⊕]. Based on the Jones matrix I built a numerical model by which the complex amplitude modulation of the LC cell could be evaluated for arbitrary elliptically polarised illumination and light detection. An elliptical polarisation can be described by two independent parameters (e.g. ratio of major and minor axes and direction of major axis) thus the illuminated and detected elliptical polarisations can be described by four independent parameters. The complex amplitude modulation of the LC cell was calculated as a function of the phase retardation in points of the four dimensional parameter-space that describes the incident and detected elliptical polarisations. The elliptical polarisations for which the LC cell realises TPA modulation were found by computer search. The searching condition was that the calculated complex amplitude modulation function must contain

[⊕] An elliptical polariser is an optical element used to generate arbitrary elliptical polarisation. One realisation is a sequence of a revolving linear polariser and a revolving quarter wave plate. An elliptical analiser is capable of transmitting one elliptical polarisation and blocking the orthogonal elliptical polarisation. It can be realised by the sequence of a revolving quarter wave plate and a revolving linear polariser.

three points of complex amplitudes A1,A2,ε with the following conditions: 0.95<|A1/A2|<1.05; 0.95π<arg(A1/A2)<1.05π; $|A1|^2/|\varepsilon|^2>15$. As the maximal phase retardation of an LC cell depends on the wavelength and different LCDs have different maximal phase retardations as well, hence the computer search was executed for more different maximal phase retardation values. By increasing the maximal phase retardation better modulation capabilities are expected. Applying an LC cell with 5.2 phase retardation TPA modulation can be obtained with an amplitude transmission of |A1|≈|A2|=0.5, namely 25% of the incident light power can be utilised. An LC cell with a phase retardation of 6 supplies TPA modulation with |A1|≈|A2|=0.6, thus 36% of the light power is utilised. An LC cell with a phase retardation of 6.6 yields TPA modulation with |A1|≈|A2|=0.9, thus 81% of the light power is utilised. In the last case |ε|=0.16 resulting a contrast ratio of $(0.9/0.16)^2=32$ between the intensities of the bright and dark states. The intensity contrast ratios in the first two cases were 15 and 16.

I made test measurement to verify the calculated results experimentally applying a transmission type twisted nematic LCD of Sony (LCX017DLT). The TPA modulation characteristics calculated for phase retardations of 5.2 and 6 were measured at 532 and 473 nm wavelengths respectively. The measured complex modulation curves were consistent with the calculations, TPA modulation could be experimentally realised with similar parameters as the calculations predicted. The intensity of the Fourier plane were compared for TPA and normal intensity modulation of 2 states applying test data bit patterns. Applying conventional intensity modulation of 2 states the ratio of peak and average intensities of the Fourier plane was 200:1, while in the case of TPA modulation it was 8:1.

Summary of new results in technical sciences

I. I recognised that TPA modulation can be realised with transmission type twisted nematic LC cells of approximately ±90° twist angle, if the LC cell is placed between an elliptical polariser and an elliptical analyser and the configurations of the elliptical polariser and analyser are optimised to the phase retardation of the LC cell.

II. I recognised that by increasing the phase retardation of the LC cell and applying an elliptical polariser and analyser optimised to the increased phase retardation the properties of TPA modulation (transmission of bright states, contrast ratio between intensities of bright and dark states) can be enhanced. I showed with numerical calculations and test measurements that with phase retardations of 5.2, 6 and 6.6 the obtainable amplitude transmissions of TPA modulation are 0.5, 0.6 and 0.9 respectively. The contrast ratios between the intensities of bright and dark states are 15,16 and 32 respectively for the above phase retardation values.

5. Publications

Publications related to the theses

1. Domján L, Kocsányi L, Richter P, Várkonyi S, Feiten W. Stripe illuminator based on LED array and parabolic mirror for active triangulation sensors used on mobile robots. Optical Engineering; 2000, 39(11): 2867-2875

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3. Domján L, Kocsányi L, Richter P, Jeszenszky É.: SNR analysis of the stripe illuminator based on linear emitter and cylindrical lens against solar irradiance. Optics and Lasers in Engineering, 2003, 40(3), p. 201

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14. Domján L, Szarvas G, Mike Sz: Optical arrangements for head-mounted displays, US patent application, 18 November 2003,

15. Domján L, Szarvas G, Mike Sz: Multiple imaging arrangements for head-mounted displays, US patent application, 18 November 2003,