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Compact Spectrometer Design as WDM-Element in POF-Communication

[1, *] M. HAUPT and [2] U. H. P. FISCHER

[1] Jade University of Applied Sciences, Friedrich-Paffrath-Str. 101, 26389 Wilhelmshaven, Germany

[2] Harz University of Applied Sciences, Friedrichstr. 57-59, 38855 Wernigerode, Germany

[1] Tel.: + 49 4421 985 2625, fax: +49 4421 985 2304

[*] E-mail: matthias.haupt@jade-hs.de

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Abstract: Optical simulation software, which is based on the ray tracing method, offers fast results in the imaging optics. This simulation method can also be applied in other fields of light propagation, such as non-imaging optics for design of optical sensor or metrology elements.

In this paper a design approach of a fully integrated miniature spectrometer by means of ray tracing simulation software is demonstrated. The basis of the presented element is a Rowland spectrometer that is optimized in crucial points, e.g. shape of mirror and grating, to guide the maximum of light. The classical Rowland spectrometers exhibit a flat design in one dimension, leading to a bad signal-to-noise ratio especially for high numerical aperture sources. Therefore, this spectrometer is designed to guide the complete light in the sagittal and tangential plane.

Further on, a monolithic approach is presented with a blazed grating based on an aspheric mirror to spectrally separate and focus light on the image layer. The aspheric mirror is designed in a way that most of the aberrations are suppressed. In general, the element should be designed in a way that it can be produced with a mass production technology like injection molding in order to offer a reasonable price. The paper will introduce the application fields of miniature spectrometers and will step by step describe the development of this fully integrated monolithic miniature spectrometer by means of ray tracing simulation.

Keywords: Raytracing, Spectrometer, Optical sensor, Visible spectrum, Miniature, Injection molding.

1. Introduction

WDM, wavelength division multiplexing, has the power to increase the data rate of standard POF, polymer optical fibers, communication dramatically [1-14]. The principle structure for WDM is shown in Fig. 1. The technology uses different channels. Each channel has its own wavelength λ_1 to λ_n. On the transmitter side these channels are combined by means of a multiplexer. Therefore, simple components, e.g. 3dB-coupler, can be used. All the different channels are transmitted over one fiber. On the receiver side a demultiplexer is used to sperate all the channels respectively wavelengths spatially.

So, it is essential to develop an inexpensive (de-) multiplexer component [15, 16]. In this paper development steps for this component based on a Rowland spectrometer are described.

Several preconditions must be fulfilled to create a functional (de-) multiplexer for POF. First, the divergent light beam, which escapes the POF, must be focused. This is done by an on-axis mirror. In the first attempt, a spherical mirror is used. To get perfect results without any spherical aberrations, an ellipsoid mirror should be preferred.

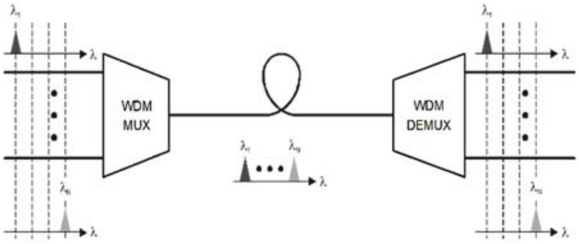

Fig. 1. WDM-Structure.

The second function is the separation of the different transmitted wavelengths. This principle is illustrated for three wavelengths (red, green, blue) in Fig. 2, respectively. This is not a limitation for possible future developments, but rather an experimental basis from where to run the various simulations described below. The diffraction is done by a diffraction grating. The diffraction is split into different orders of diffraction. The energy guide should be optimized for one order of diffraction to regain all information. A detector line can be installed there to detect the signals.

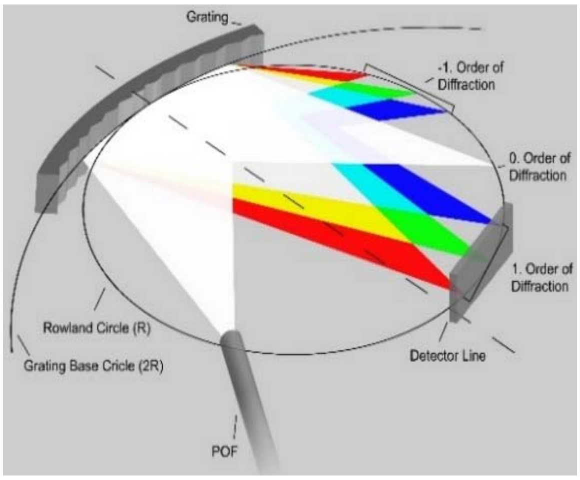

Fig. 2. Principle sketch of a Rowland Spectrometer.

Because the grating is attached to a bended basement only one element can cover both functions, focusing and diffracting. Hence the light is not afflicted with any aberrations or attenuations of a focusing lens or other dif/re-fractive elements, which are necessary for any other setup.

Another unique characteristic of the presented key element for POF communication is the three-dimensional approach. Key elements of glass fiber communication are usually designed planar. This simplification cannot be adopted for POF communication, because of the large Numerical Aperture and therefore large opening angle of the POF. A planar setup for POF key elements would lead to high losses.

1.1. Advantages of Polymer Optical Fibers

Polymer Optical Fibers (POF) offer many advantages compared to alternate data communication solutions such as glass fibers, copper cables and wireless communication systems. In comparison with glass fibers, POF offer easy and cost-efficient processing and are more flexible for plug interconnections. POF can be passed with smaller radius of curvature and without any mechanical disruption because of the larger diameter compared to glass fibers.

The advantage of using glass fibers is their low attenuation, which is below 0.3 dB/km in the infrared range. In comparison, POF can only provide acceptable attenuation in the visible spectrum from 400 nm up to 700 nm, see Fig. 3. The attenuation has its minimum with about 85 dB/km at approximately 570 nm. For this reason, POF can only be efficiently used for short distance communication up to 100 m and the disadvantage of the larger core diameter is higher mode dispersion.

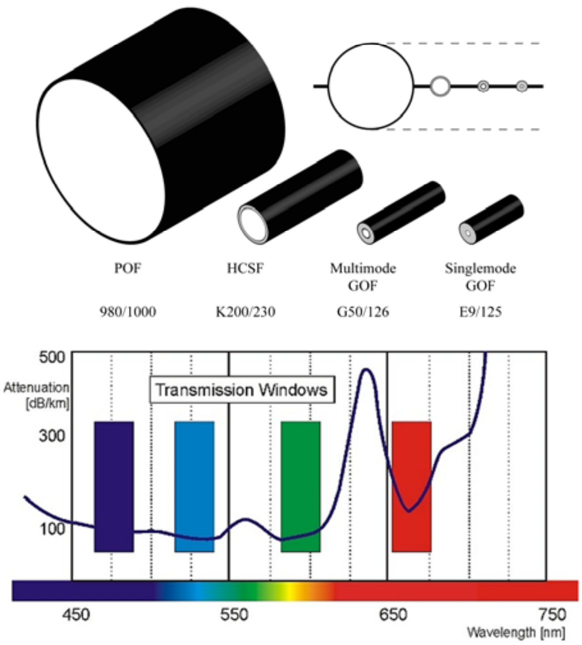

Fig. 3. Principle and attenuation of POF in the visible range [1]

The use of copper as communication medium is technically outdated, but still the standard for short distance communication. In comparison, POF offers lower weight and space. Another reason is the nonexistent susceptibility to any kind of electromagnetic interference [1-3].

Wireless communication is afflicted with two main disadvantages. The electromagnetic fields can disturb each other and probably other electronic devices. Additionally, wireless communication technologies provide almost no safeguards against unwarranted eavesdropping by third parties, which makes this technology unsuitable for the secure transmission of volatile and sensitive business information.

2. Results of the Simulation

In the following steps, a software program is used to design a demultiplexer based on the general concept of a Rowland Spectrometer. For the current task, the software OpTaLiX provides all required functionalities [17]. This approach offers different advantages, it is easy to design, analyze and evaluate the simulated results. In addition, effective improvements of the configuration can be simulated quickly.

In Fig. 4, the 2D plot for the reference wavelength (520 nm) of the spectrometer with an ellipsoid mirror and grating is shown. The multicolored light is emitted by a polymeric fiber. It hits the mirror, where it is focused and diffracted in its monochromatic parts. The light is focused onto a POF- or detector-array.

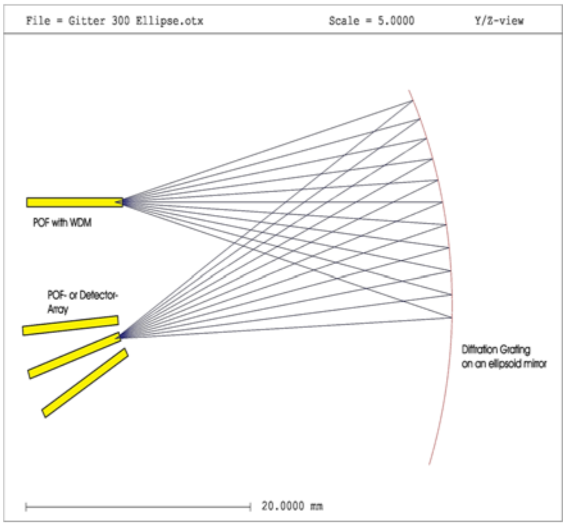

Fig. 4. 2D plot of the demultiplexer.

Without a grating, a perfect point-to-point mapping (without any aberrations) is possible with an ellipsoid mirror because of the two focal points, but there is no separation of the different channels. With a grating stamped on the mirror, the separation of the multicolored light in its monochromatic parts is possible. But this grating distorts the optical path of light dramatically.

The gap between the different colors in the image layer (here the POF- or Detector Array) increases with the line density of the grating, see Fig. 5 and Fig. 6. This can be noticed for an ellipsoid mirror (Fig. 4) and for a spherical mirror (Fig. 5) as well. The spherical mirror has the advantage, that the shape for injection molding can be produced more easily.

The second change is the strong astigmatism behavior especially for the demultiplexer with high line density. To emphasize this result and to analyze the aberrations in detail, the transverse ray aberration (TRA) and the optical path difference (OPD) in spectrometer mode are shown in Fig. 7 and Fig. 8 for the demultiplexer with an ellipsoid mirror and 1200 lines/mm. The chief ray coordinates are irrespective for the TRA and OPD to overlap the different colors.

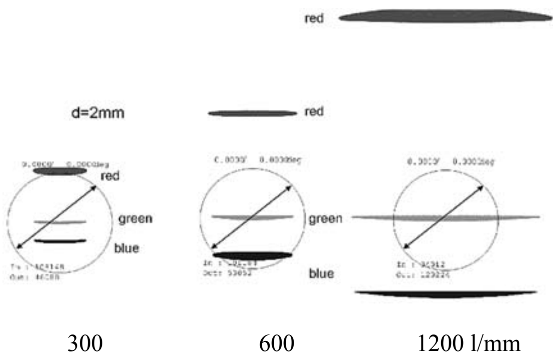

Fig. 5. 2D Plot of the demultiplexer with an ellipsoid mirror.

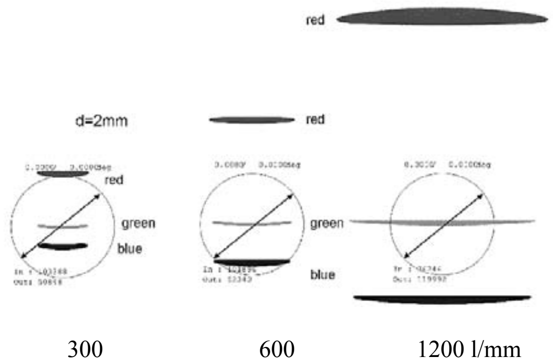

Fig. 6. 2D Plot of the demultiplexer with a spherical mirror.

The TRA (Fig. 7) shows a slight defocusing for the meridional (tangential) section, but a strong defocusing for the sagittal section. The graph of the function in the meridional section exhibits a predominant third order Seidel coefficient. Therefore, the slight defocusing in the meridional section compensates the astigmatism. The OPD (Fig. 8) shows as expected strong deviation from the ideal waveform, especially in the sagittal section. This defocusing leads to high losses for the coupling efficiency for the POF- or detector- array in the image layer.

It is obvious that the grating changes the focal length especially of the sagittal section; therefore, the shape of the mirror must be improved. It is necessary to change the radius of curvature notable in the sagittal section. Hence the basic shape of the mirror is no longer a sphere or ellipsoid. To meet the demands a higher order shape, which is nearly cylindrical, is used.

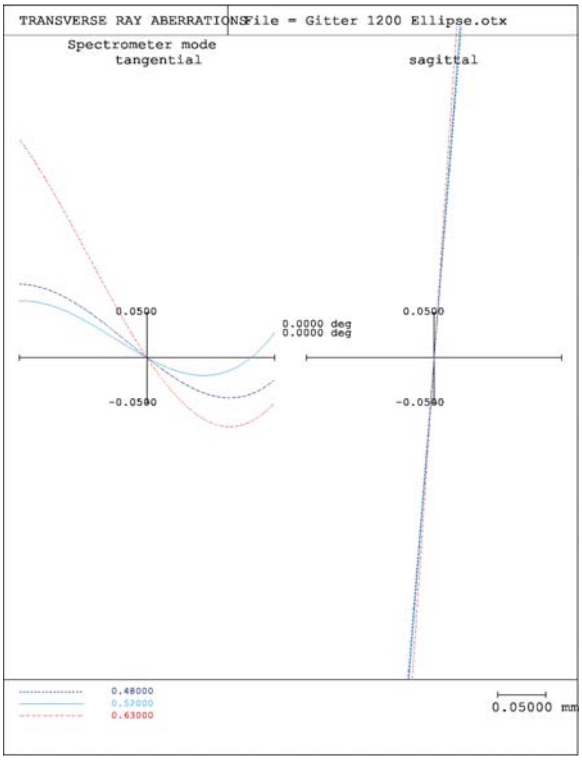

Fig. 7. TRA for the ellipsoid demultiplexer with 1200 lines/mm.

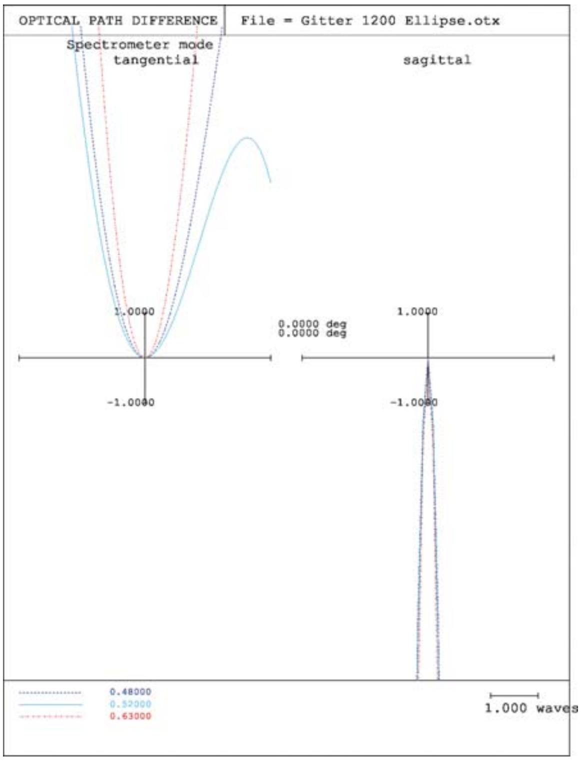

Fig. 8. OPD for the ellipsoid demultiplexer with 1200 lines/mm.

The change of the mirror shape improves the imaging quality substantial. The Spot Diagram and the TRA for the improved demultiplexer are shown in Fig. 9 and Fig. 10.

The Spot Diagram shows three dividable colors for all line densities. The gap improves with the line density and at 1200 lines/mm the gap between every color is larger than 2 mm. The TRA shows a marginal shift of the focus of all wavelengths to offset the astigmatism in the meridional section. Because of the spectrometric function of the demultiplexer it is not possible to focus all three colors simultaneously. There is always a combination of over- and undercorrection for the different colors. Hence the radius of the mirror in the sagittal section is optimized to focus the colors in whole as much as possible.

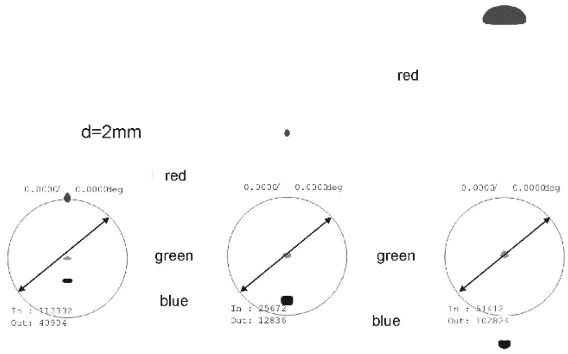

Fig. 9. Spot Diagram (circle diameter 2 mm) for the improved demultiplexer.

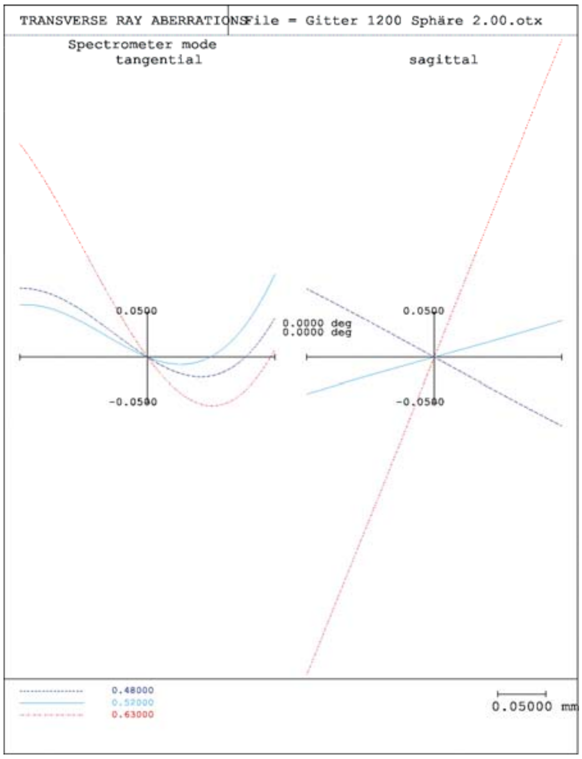

Fig. 10. TRA for the improved demultiplexer.

This improved spectrometer can separate three colors with enough space between them to regain the information with a POF - or detector-array. Hence it can be used as a demultiplexer for POF communication. The shapes of the foci feature low coupling losses and the shape of the mirror should be easy to produce by injection molding.

2.1. Grating Efficiency for Different Diffraction Orders

Focusing of the light is one part of the setup. The other task is separating the different wavelengths. Both of them is done by a dispersion grating based on an aspheric mirror. This grating can only be optimized for one order of diffraction. A simple linear grating guides most of the light into the first diffraction order. To reduce the line density of the grating for better manufacturing possibilities a higher order (second or third) should be used instead. Therefore a blazed grating must be applied. This Littrow configuration optimizes the light guidance in a higher diffraction order. But this kind of grating can only be improved to nearly 100 % for a single wavelength. It is common to use a green peak wavelength for the whole visible spectrum to get the best efficiency. The result of this optimization of the grating is shown in Fig. 11 for the first, the second and the third diffraction order.

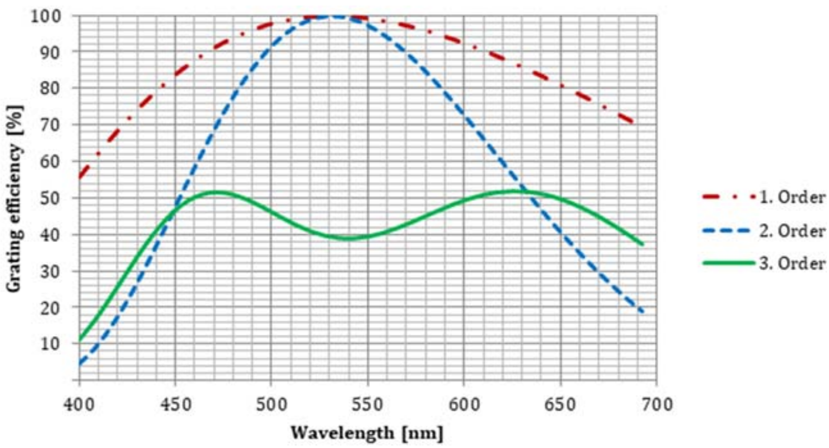

Fig. 11. Grating efficiency for different diffraction orders.

The first order of diffraction exhibits the best efficiency. The value is above 60 % for the complete visible spectrum, but is not applicable in our case due to problems with the fabrication. The second order of diffraction offers more than 40 % of efficiency in the range from 450 nm to 650 nm. The third order has two maxima: at 470 nm and 630 nm to cover a larger wavelength range, but the efficiency is not higher than 50 %. That means 3 dB of the power will be lost just for the grating. This is too much for the insertion loss of this component. Consequently the second order seems to be the only suitable order of diffraction. This is not the only reason for the use of the second order. Third and higher orders will be overlapped in the visible region by lower orders and this will cause crosstalk.

2.2. Examination of Image Layer for the Blazed grating

The shape of the foci in the detection layer will not be changed dramatically by optimizing the grating. The higher the line density the larger is the gap between the colors. But this will also lead to greater aberrations. Therefore, it is easy to find the right line density for the grating. The line density of the grating must be high enough to separate every color in the image layer. So the distance must be at least 0.5 mm between the blue and the green focus point and also between the green and the red focus point. Higher line densities would lead to greater aberrations and to more problems in the fabrication process. The image layer for the second order of diffraction and a line density of 500 l/mm is shown in Fig. 12 and Fig. 13. These parameters fit well the requirement. An additional fourth color with a wavelength of 405 nm is added. Also the radii in the x- and y-axis are optimized to suppress the astigmatism caused by the Rowland spectrometer setup. This works well in one direction but in the other direction the astigmatism will remain even for the optimized setup.

3. Conclusion

The spot diagram can only give a hint of the real size of the focus points, because the rays were sent through the optical systems by an ideal source. But in the setup the source will be a POF, with a core diameter of 0.98 mm. This will lead to larger focus points. To get a realistic estimation, the simulation is enhanced to an area light source with a diameter of 0.98 mm. The result can be seen in Fig. 14.

State of the art for POF communication is the use of only one single channel. This means a limitation of bandwidth. The solution for this bottleneck is WDM over POF, as not only one channel is used to transmit information over a single fiber. To use this technique two key elements must be designed completely new: a multiplexer and a demultiplexer, because the key elements of the established WDM for glass fibers in the IR cannot be applied.

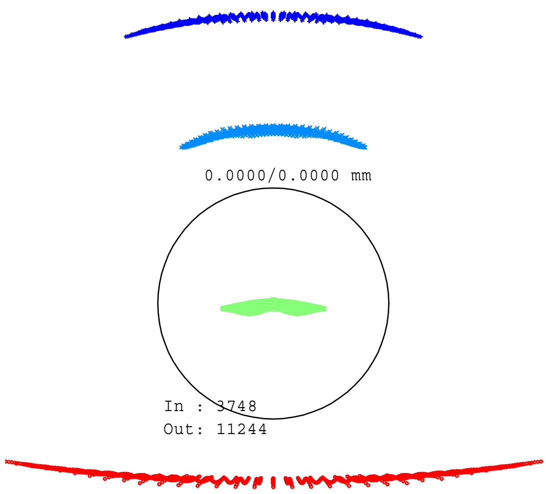

Fig. 12. Spot diagram (not optimized, circle diameter 1 mm).

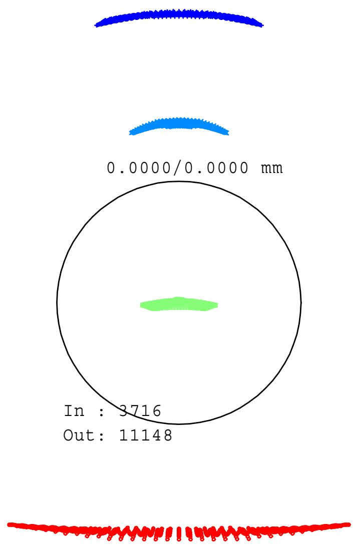

Fig. 13. Spot diagram (optimized, circle diameter 1 mm).

The simulation results show that it is possible to build up a demultiplexer by means of a Rowling Spectrometer. A special shape of the mirror is required to suppress most of the aberrations caused by the grating. The improved demultiplexer can separate all three colors with a gap of 2 mm and a crosstalk of less than 30dB. So, in combination with injection molding this configuration can be produced with sufficiently costs. This spectrometer has the chance to increase data rate of standard POF communication also with a broad range of usability in optical spectroscopy for sensor systems in automotive and medical applications due to its low-cost realization.

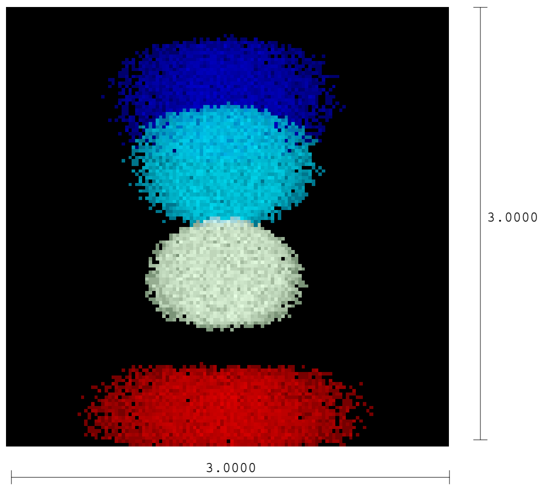

Fig. 14. Image layer of the setup for an area light source.

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