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► **To cite this version:**

Fannie Castignoles, Thierry Lépine, Pierre Chavel, Gilbert Cohen. Shack-Hartmann multiple spots with diffractive lenses. *Optics Letters*, Optical Society of America, 2011, 36 (8), pp.1422-1424. <10.1364/OL.36.001422>. <ujm-00586811>

HAL Id: ujm-00586811

<https://hal-ujm.archives-ouvertes.fr/ujm-00586811>

Submitted on 6 Apr 2012

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Shack–Hartmann multiple spots with diffractive lenses

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Received February 22, 2011; accepted February 23, 2011;

posted March 21, 2011 (Doc. ID 142766); published April 13, 2011

In this Letter we aim to bring an understanding to the apparition of multiple spots when using a Shack–Hartmann (SH) wavefront sensor behind diffractive lenses. In contrast to previous work, this phenomenon is described in terms of diffractive orders. It is illustrated with Zemax simulations, where three kinds of diffractive lenses (monofocal, bifocal, and trifocal) are set behind a microlens array. The presence of multiple spots is related to the phase jump of the diffractive profile and also to the number of steps seen through the microlens pupil. The possibility of assessing the optical quality of such lenses using SH measurements is discussed, in particular within the field of ophthalmology, where the need for precautions is underlined. © 2011 Optical Society of America

OCIS codes: 050.1965, 170.4470, 040.1240.

When measuring diffractive lenses behind a Shack–Hartmann (SH) wavefront sensor, it has been shown that multiple spots can appear [1–3]. Physically misunderstanding that effect can lead to wrong conclusions about the optical quality of such lenses. This is particularly true in ophthalmology, for example, for patients with diffractive intraocular implants after operations for cataract that correct presbyopia at the same time [4].

While Schwiegerling and DeHoog [1] have complemented previous medical publications [1–5] by physically investigating the effect, we shed new light by directly relating the spot pattern obtained on an SH behind a diffractive lens with diffractive orders rather than only with the number of phase jumps in a given SH pupil, as was in fact already explained by Charman *et al.* [3]. That has, in turn, a direct implication on the number of spots observable and its changes with wavelength, which we analyze quantitatively for the first time. We further illustrate the effect by using Zemax simulations with several kinds of diffractive lenses [6].

Figure 1 shows the three diffractive lenses studied: a monofocal diffractive lens, a bifocal lens, and finally a trifocal diffractive lens. These three lenses consist of a parabolic diffractive profile (with addition powers ranging from -3D to $+3\text{D}$) added to a carrier biconvex refractive lens with a common power of $+20\text{D}$. The diffractive profile is made of annular zones of decreasing width from the center to the periphery, separated by steps of equal height. The step height is chosen so that, at a specified design wavelength, the phase difference between two side-by-side rays leads to constructive interferences in one, two, or three foci [7].

The effect of these diffractive lenses can be described with an expansion in a Fourier series, each term of the series being one diffracted order. The diffractive efficiency in each order depends of the height of the steps. Thus, at design wavelength, the monofocal, bifocal, and trifocal lenses have respectively one, two, and three diffracted orders with nonnegligible diffractive efficiencies. One may expect each diffractive order to lead to one spot behind each SH lenslet. However, in reality, three situations have to be considered: either the microlens inter-

cepts light from several steps, or just one step, or finally, only the central zone.

If the microlens pupil intercepts several steps, the diffractive lens can locally be considered to be a grating. It is therefore easy to understand that a spot will appear for each diffractive order. The multiple spots are more separated for smaller zone widths, which corresponds to the diffractive lens periphery.

In the second situation where the pupil of the microlens intercepts only one step, light from the two zones interferes and forms a set of maxima and minima, which

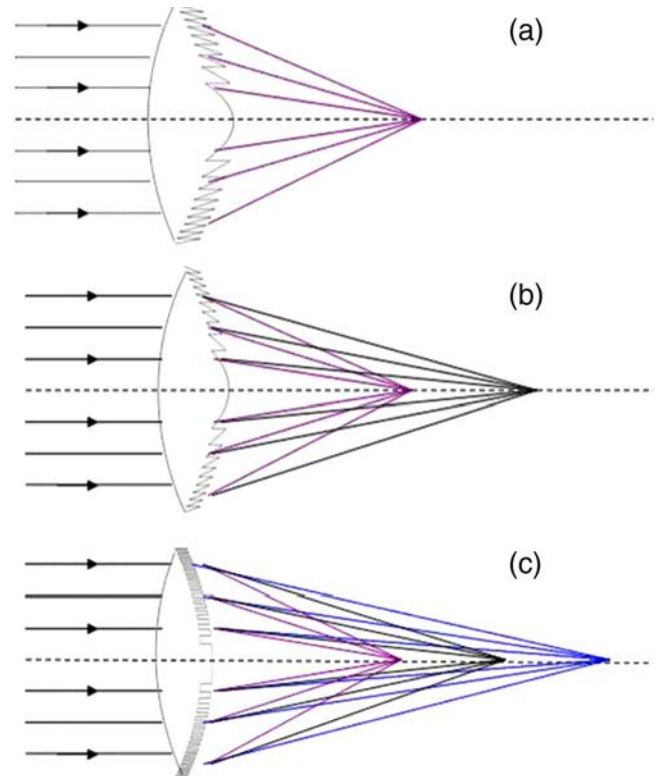


Fig. 1. (Color online) Three diffractive lenses used for Zemax simulations: (a) monofocal lens ($P = +23\text{D}$), (b) bifocal lens ($P = +20\text{D}/ +23\text{D}$), and (c) trifocal lens ($P = +17\text{D}/ +20\text{D}/ +23\text{D}$).

can formally be analyzed as resulting from the diffractive orders, although they overlap and are not well separated.

Finally, in the case where the pupil intercepts only one zone—typically the central zone, no interferences between the rays of different steps can be produced, so that only a single spot will result, whatever type of diffractive lens is used. In fact, in this case the coherent sum of the different diffractive orders can be shown to equate a single wave corresponding to the curvature of the central zone.

We will now present numerical illustrations of these different situations with Zemax simulations. Our model is illustrated in Fig. 2.

It is composed of one diffractive lens and of the microlens matrix of the SH wavefront sensor placed 20 mm behind the diffractive lens. The number of microlenses has been significantly reduced compared to real SH sensors for the sake of faster calculation and clearer illustration. Each microlens is 0.25 mm on each side. The lenses are illuminated by an incident planar wavefront at the design wavelength $\lambda_{\text{design}} = 550$ nm, which corresponds to the photopic vision. The results of the simulations are observed in the focal plane, 6 mm behind the microlens array. The physical optics propagation mode of Zemax is used to propagate the light through our model.

Figure 3 shows the results obtained from the different simulations. The grid shows the microlens boundaries, with crosses drawn in their centers. This enables a clearer observation of the convergence of the spots toward the center of the field, which is due to the combined diffractive and refractive power. In Fig. 3(a), which corresponds to the monofocal lens, only single spots are present behind each microlens. Thus, despite the presence of several steps through the pupil of some microlenses, we do not observe multiple spots. On the other hand, except in the central microlens, double spots are visible in the bifocal lens simulation in Fig. 3(b). Finally, the simulation of a trifocal diffractive lens [Fig. 3(c)] leads to triple spots belonging to the three foci.

These simulations allow us to definitively prove wrong the view that multiple spots appear if a microlens intercepts at least more than one step, as if each step gave its own spot. That is demonstrated in a particularly clear way in the monofocal lens case.

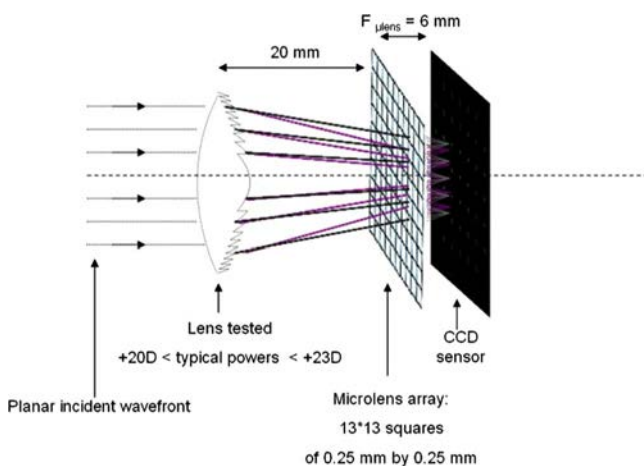


Fig. 2. (Color online) Model of the diffractive lens measured by an SH sensor.

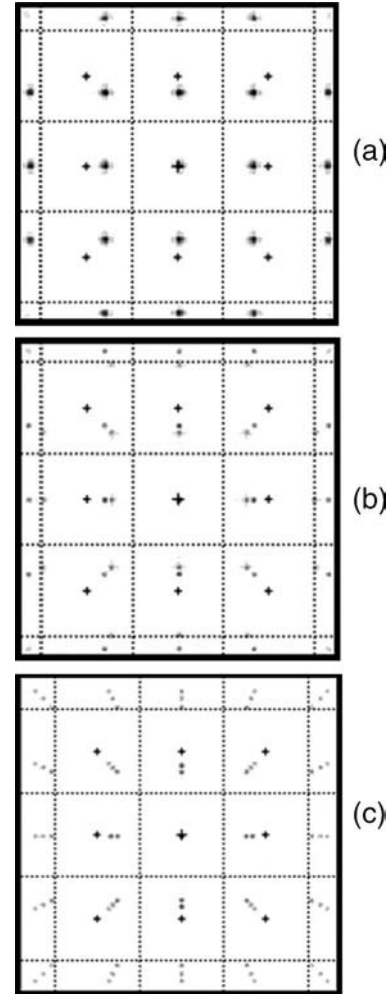


Fig. 3. Simulation of the spots with an SH sensor behind a (a) monofocal lens, (b) bifocal lens, and (c) trifocal lens.

In fact, at λ_{design} , the apparition of multiple spots depends upon two conditions. Multiple spots appear if, first, the microlens intercepts at least one phase jump so that interferences take place, and second, the phase shift is different from 2π , leading to partly constructive interferences in multiple orders. In fact, for each diffractive order with a nonnegligible diffractive efficiency, one spot will appear behind each microlens. It is therefore possible to distinguish two families of spots in the case of the bifocal diffractive lens, and three families behind the trifocal one. However, in the central zone only a single spot is visible in all cases, as was discussed above, because the central microlens (of diameter 0.25 mm) intercepts only a part of the beam emerging from the central zone (this beam has a diameter 0.5 mm on the SH sensor).

These simulations allow us to understand the apparition of multiple spots on an SH sensor behind a diffractive lens, at λ_{design} .

Additional caution is required when the measurements are not conducted at λ_{design} . This is particularly the case in ophthalmology, where the SH can be used to measure the eyes of patients who have been corrected of presbyopia with a diffractive intraocular lens. In fact, in order not to dazzle the patient, it is common practice to use IR light with a wavelength between 780 to 800 nm. But the diffractive efficiencies of diffractive lenses strongly

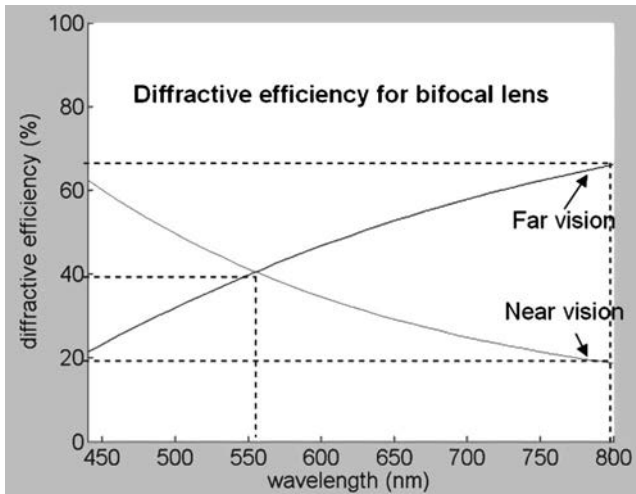


Fig. 4. Diffractive efficiency of a parabolic bifocal diffractive lens versus wavelength.

depend on the wavelength. For example, in the case of a bifocal diffractive parabolic [6] lens (Fig. 4), we can see that at λ_{design} , the diffractive efficiencies of the two foci are both equal to about 40%, while near 800 nm the diffractive efficiency of the far vision focus is about 60% against 20% for the other.

Therefore in this latter case, the family of spots corresponding to the near vision can be scarcely visible or even not visible at all, and thus single spots can result from SH measurements. Still it is necessary to take all the spots into account to enable a correct characterization of the lens. For instance, the modulation transfer

function (which characterizes the optical quality of an optic and can be deduced from the SH measurements) of a bifocal lens at one of its two foci is damaged by the presence of the other defocused order [7]. Thus if the spots corresponding to this order are not taken into account in an SH measurement, this will lead to overoptimistic results.

In conclusion, multiple spots in the SH diagram of a diffractive lens arise from the diffractive orders and are not related in a simple way to the existence of a step inside the SH microlens. Also, furthering the conclusion of [2], a diffractive lens must be characterized by using the complete set of spots, and the wavelength dependence of diffraction efficiency cannot be ignored when exploiting characterization results. The development of specific SH aberrometers, or at least of specific software for diffractive lenses, appears to be required.

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