Pupil apodization for increasing data storage density

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We introduce a technique for increasing density in optical data storage systems. This technique is based on the use of a superresolving filter at the pupil of a confocal readout system. The main characteristic of this confocal readout system is that the light beam traverses twice through the pupil filter. We describe how to analyze the system performance for general filters, but we focus the study on filters with no focus displacement. Although the storage density attainable depends on the filter characteristics, we show that the storage density can be easily duplicated.

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Data storage is an increasing market, because there are more and more applications that require electronic archives, due to their better accessibility and lower costs. Two decades ago, it seemed as if optical devices were to beat the rest of storage technologies, but magnetic and semiconductor devices have evolved more quickly than optical ones and, consequently, optical storage systems do not dominate the market but complement the other technologies. The most relevant characteristics of storage devices are the cost, transfer rate, data density, and durability. Of course, it depends on each application which of these characteristics is more relevant and, accordingly, which storage technology is preferred. At the moment, optical systems cannot compete in terms of data density or transfer rate, but their low cost and easy reproducibility make them useful for information distribution and archiving applications in the domain of personal computers. In this situation, optical storage systems must improve their performance in order to succeed further in this growing market. In this letter, a confocal set up for improving data storage density in optical devices is described and analyzed. It is based on the modification of the pupil function of the system by using of a superresolution mask[1].

The design of pupil masks for point spread function (PSF) engineering has been approached from different points of view in several applications, such as confocal microscopy, astronomy, lithography, free space communications, and even in optical data storage[2−5]. Radial-symmetric filters have been usually preferred for ease of their fabrication and analysis. The first designs are based on amplitude masks, but hybrid[6] and phase-only masks[1] are now more generally studied and, especially, binary phase-only annular profiles stand out for their simplicity and good performance[7−9]. The design of these masks basically consists in the definition of some figures of merit that describe the desired focal light distribution, and the calculation of the filter parameters from these figures of merit. For optical data storage, the first designs searched for transverse superresolution and a larger focal depth[2], but recent devices require several layers and, thus, three-dimensional (3D) superresolution is preferred[10−13]. For this reason, the combination of a confocal system and a transverse superresolving filter is an optimum choice for attaining the best performance from optical devices[3].

The proposed scanning scheme is shown in Fig. 1. The light from the source is focused sequentially at each point of the optical disc by a lens, whose pupil is modified by the superresolution filter. The reflected light traverses again through the lens and the filter, and is finally collected by a confocal detector. Suppose that the numerical aperture of the objective is not too high and consequently, the scalar diffraction theory can be used (the case of high numerical aperture will be discussed later). Then, the transverse amplitude PSF at the focal detector plane can be expressed as[3,14]

$$U(v) = h(v)h(v), \tag{1}$$

where v is a radial dimensionless optical coordinate given by $v = k\ \mathrm{NA}\ r$ ($k = 2\pi/\lambda$, where λ is the wavelength, NA is the numerical aperture of the pupil, and r is the radial distance), h is the amplitude PSF that corresponds to the lens and the filter, expressed as

$$h(v) = 2\int_0^1 P(\rho)J_0(v\rho)\rho\mathrm{d}\rho, \tag{2}$$

where ρ is the normalized radial coordinate over the circular pupil and P is the pupil function. The PSF can be obtained from $I(v) = |U(v)|^2$. Note that this

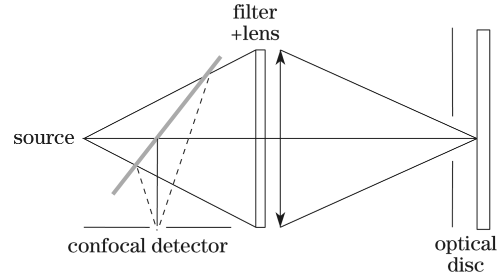

Fig. 1. Scanning scheme proposed for increasing storage density.

PSF is the square of the PSF corresponding to the same lens and filter in a conventional (non-confocal) setup[14]. This fact suggests that the proposed PSF will increase the resolution and decrease the sidelobes at the expense of energy.

For analyzing the PSF characteristics, we use known figures of merit such as the Strehl ratio, the sidelobe intensity, and the transverse superresolution gain factor[1]. The Strehl ratio S is defined as the ratio of the intensity at the focal point (the detector in Fig. 1) to that corresponding to an un-obstructed pupil. The sidelobe intensity I_{r} is defined as the maximum intensity of the first ring in the superresolution intensity pattern relative to the peak intensity. It is desirable to maintain this value as low as possible. Usually, values greater than 30% of the peak intensity are not acceptable for data storage[2,13]. Finally, the transverse gain gives a measure of the superresolution performance in the transverse direction. It is normalized to make the un-obstructed pupil equal to unity[1], while it is greater than unity when it yields superresolution. This gain is based on the second-order approximation of the PSF and the application of the Rayleigh criterion to such parabola. It is a commonly used parameter for transverse resolution because it yields useful information and can be calculated from the pupil moments[1]. Furthermore, this gain is inversely proportional to the square of the spot radius[1] and, consequently, it is directly proportional to the storage density. Due to its central role, we will check its validity by comparing it with the application of the Sparrow criterion for the PSF with no approximation (for the latter PSF, the Rayleigh criterion does not provide useful information).

In order to calculate these parameters, we expand the intensity distribution in series near the geometrical focus.

$$\begin{aligned} I(v) &= \left| \left[I_0 - \frac{1}{2} I_1 \, v^2 + O(v^4) \right] \right. \\ &\quad \left. \left[I_0^* - \frac{1}{2} I_1^* v^2 + O(v^4) \right] \right|^2 \\ &\approx |I_0|^4 - Re\,(I_0 I_1^*)\; |I_0|^2 \, v^2, \end{aligned} \tag{3}$$

where * denotes complex conjugate and I_n is the nth moment of the pupil function, defined as

$$I_n = 2 \int_0^1 P(\rho) \cdot \rho^{2n+1} \mathrm{d}\rho. \tag{4}$$

In the general case, the maximum of the axial intensity can be displaced when a filter modifies the pupil. However, we focus on real filters (amplitude, $0-\pi$ phase filters or a combination of both), where the focus displacement is zero and can yield a wide range of behaviours[7,11−13]. In such case, the Strehl ratio and the transverse gain become

$$S = |I_0|^4 \,, \tag{5}$$

$$G_{\mathrm{T}} = 4 \, \frac{I_1}{I_0}. \tag{6}$$

Note that the gain is multiplied by the same normalization factor used in the non-confocal case[12], i.e., 4, in order to compare both cases in identical conditions. As previously predicted, there is a decrease of the core energy but at the same time the transverse gain is twice the gain of the non-confocal case (the width of the parabola in the confocal case is half width of the parabola in the non-confocal case). While Eq. (5) is exact, Eq. (6) is based on the second order approximation of the PSF. In the case of the other figure of merit, I_{r}, the PSF must reach the v^{12} term, and, thus, it is not useful to search for an expression in terms of the moments of the pupil function. It is a common design procedure to obtain the filter parameters in terms of the Strehl ratio and the resolution, and to check whether the corresponding value of the sidelobe height is acceptable[12]. In a confocal system, this design procedure is even more justified than in the non-confocal case.

For the filters here considered, analytic expressions can easily be derived for Eqs. (5) and (6). For example, for two-zones filters with intermediate radius ρ_1, t amplitude transmittance in the inner zone and 1 in the outer zone, the Strehl ratio is $S = [1+(t\text{-}1)\rho_1^2]^4$, the transverse gain is $G_{\mathrm{T}} = 4\,[1+(t\text{-}1)\rho_1^4]/[1+(t\text{-}1)\rho_1^2]$, and even the PSF can be analytically expressed as

$$I(v) = \left[2\frac{J_1(v)}{v} - 2\,(1-t)\;\frac{\rho_1 J_1(\rho_1 v)}{v} \right]^4. \tag{7}$$

Note that the amplitude transmittance varies from 1 to -1, where the positive values correspond to amplitude filters and the negatives ones to hybrid filters. The special case of phase-only filters is achieved when $t = -1$. Let us analyze the system behaviour for the latter filters. We calculate the PSF for several values of the radius between zones. As an illustrative example, Fig. 2 shows the PSF corresponding to radius $\rho_1 = 0.3$. For comparison, the non-confocal case and the pupil free PSF are also represented. In every case, the second-order approximation, which is used for the gain estimation, is also shown. From these PSFs, the gain can be represented as a function of the radius between zones, as shown in Fig. 3. We can extract several consequences from this figure. Firstly, the gain for the confocal system is better than that for the conventional system for every radius in the superresolution regime ($\rho_1 < 1/\sqrt{2}$)[12]. Secondly, the gain obtained from the second order approximation of the PSF using the Rayleigh criterion is very similar to that obtained from the Sparrow criterion on the exact PSF, which reinforces the use of G_{T} as a valid parameter for image resolution. Finally, as expected, the gain increases asymptotically as the value $1/\sqrt{2}$ is approached. However, the next figure shows that this increase is accompanied by an energy loss at the PSF core. Figure 4 represents the Strehl ratio as a function of the attained transverse gain, and as predicted, the Strehl ratio decreases as the gain increases. This curve for two-zones $0-\pi$ filters can be easily derived in the superresolution regime ($G_{\mathrm{T}} > 1$) as

$$S = 1 + 2(1-G_{\mathrm{T}})\left[(1-G_{\mathrm{T}}) + \sqrt{1+(1-G_{\mathrm{T}})^2}\right]. \tag{8}$$

The most relevant conclusion is that, once the Strehl ratio value is fixed, our confocal system yields better resolution than non-confocal systems in the superresolution range $G_T \in (1, 4.5)$, approximately. On the other hand, the non-confocal system performs better for extreme transverse gain ($G_T > 4.5$), but for such filters, the Strehl ratio is so low and the sidelobes are so high that it is not feasible for the system being used. Once again, the results obtained from the Sparrow criterion fit well with those derived from G_T.

Finally, the sidelobe behaviour must be analyzed. Figure 5 represents the sidelobe ratio as a function of the

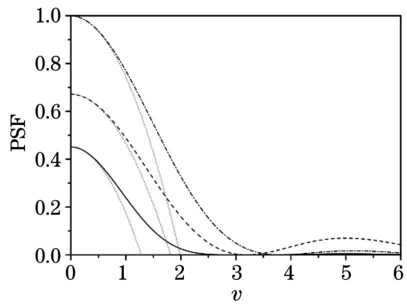

Fig. 2. PSF corresponding to a 0−π phase-only filter with radius $\rho_1 = 0.3$ (solid curve). For comparison, the non-confocal case (dashed curve) and the pupil free (dotted-dashed curve) PSF are also represented. In every case, the second-order approximation, which is used for the gain estimation, is also shown (dotted curves).

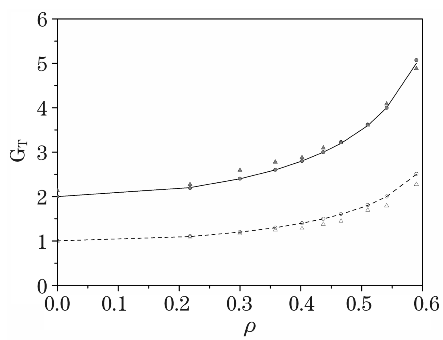

Fig. 3. Theoretical transverse gain as a function of the radius between zones in the confocal (solid curve), Eq. (6), and non-confocal (dashed curve) case. Values of this gain calculated from the PSF are also shown in the confocal (circles) and non-confocal case (empty circles). Finally, the estimation of the gain using the Sparrow criterion is shown in the confocal (triangles) and non-confocal case (empty triangles).

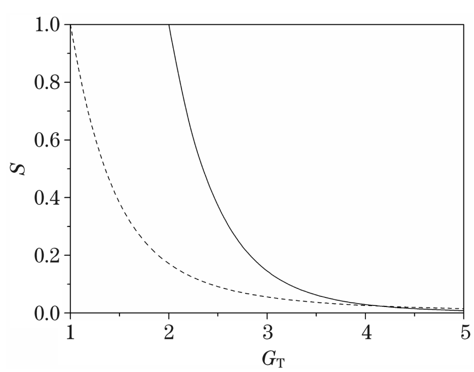

Fig. 4. Strehl ratio as a function of the transverse gain for the confocal system (solid curve) and the non-confocal system (dashed curve).

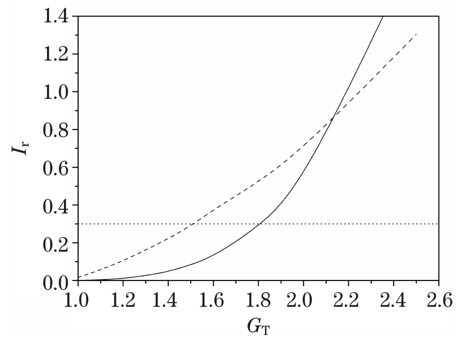

Fig. 5. Sidelobe ratio as a function of the transverse gain for the confocal system (solid curve) and the non-confocal system (dashed curve).

transverse gain for binary 0−π phase-only filters. It can be seen that the confocal system yields a better value for the whole range of interest ($I_r < 0.3$). Furthermore, the figure shows that the sidelobe value limits the attainable gain to a value of ~1.8. For each type of filters, this curve should be built. In any case, all the filters proposed for the sidelobe ratio improvement[6] could be used in the confocal system, where their performance would be enhanced. An additional improvement for sidelobe ratio could be obtained by the use of two slightly different filters instead of only one. This would require a different design (with a more complicate alignment), but it could be a solution for cases in which a very high gain is required.

The whole analysis can be extended to the case of high numerical aperture, which is relevant as some of new storage systems have high NA[10]. In the transverse direction, a useful expression for the amplitude PSF can be found by use of the scalar high-aperture approximation instead of the vectorial theory[15]. In such case, the PSF in terms of the pupil moments can be expressed as

$$I(v) \approx |Q_0|^4 - \frac{\mathrm{Re}\,(Q_2 Q_o^*)}{4\sin^2\alpha}\ |Q_0|^2\, v^2, \tag{9}$$

where α is the semiaperture angle, and the moments Q_n are defined as in Ref. [16]. This leads to a gain which is again twice the gain of the non-confocal case and a Strehl ratio which is the square of that corresponding to the non-confocal case. Consequently, most of the conclusions derived in the previous case are still valid for high aperture systems, and the presented analysis can be used for investigating their performance.

In conclusion, we present a confocal readout setup that, by use of a superresolution filter, allows a relevant improvement of data density in optical data storage systems. With the setup, full disk recordings of 2TB could be possible within a standard form factor of 120×1.2 (mm) thick if current technology is stressed to its limits. We analyze the resolution, the energy loss, and the sidelobe behaviour for real filters. And in the case of 0−π phase filters, we show the superresolution range where useful results can be attained. Furthermore, analytic expressions for the Strehl ratio, the transverse gain, and the PSF are derived. Finally, we demonstrate that the proposed setup is also valid for high aperture systems.

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