Nonredundant array of apertures to measure the spatial coherence in two dimensions with only one interferogram

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We propose to use a mask with a nonredundant array (NRA) of multiple apertures to measure spatial coherence in two dimensions. The spatial distribution of the apertures in the mask is made in such a way that we obtain a quasi-uniform sampling in the coherence domain. The spatial coherence is obtained by Fourier transform of the interferogram generated by the mask when it is illuminated by the light field under analysis. © 2011 Optical Society of America

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1. INTRODUCTION

The standard method for measuring the spatial coherence of the light field is based on the double-aperture interferometer (Young experiment). By moving the double-aperture mask and changing the spacing and orientation of the apertures, we can measure the spatial coherence of the entire light field in a given plane. To obtain a large quantity of coherence data on a cross section of the light field, we have to perform a large number of Young experiments (as many experiments as coherence data are required). Some refined techniques based on the double-aperture interferometer have been developed, for instance, the reverse-wavefront Young interferometer [1]. In this technique, two replicas of the light field are created using a beam-splitter cube. These light fields emerge parallel and propagate in the same direction, and then they impinge onto a double-aperture mask. In this case, the distance between the apertures is fixed. To measure the spatial coherence for different pairs of points, the separation of the two replicas is changed by moving the beam splitter cube laterally. The advantage of this method is that the coherence data can be taken sequentially, reducing the acquisition and processing time.

In 2007, we proposed a method for measuring the spatial coherence of light fields from only one interferogram [2]. By illuminating a mask with a one-dimensional array of apertures with the light field under analysis, we register the far-field interferogram in a CCD camera. The spatial coherence is measured from the Fourier spectrum of the interferogram. The Fourier spectrum is interpreted as a distribution of peaks whose position (except the central peak) is given by the separation vectors of the aperture pairs that result from the array. The height of these peaks depends on the multiplication of the intensities in the apertures and the spatial coherence of aperture pairs. The phase of these peaks determines the phase of the spatial coherence. We also showed that if the coherence of the light field is shift variant, the array of apertures must be nonredundant (NRA). Subsequently, we proposed an extension of the method for two dimensions [3]. The mask used consists of an NRA of five apertures in the x axis and the same NRA in the y axis (we rotated 90° the NRA located in the x axis). In this manner, we achieve a quasi-uniform sampling in the x and y directions in the Fourier spectrum, but a poor sampling in other directions.

The key of our method is the relation of the Fourier components with the set of Young interferograms produced simultaneously using a mask of multiple apertures. This idea has been used before by other authors. For instance, in 1963, Rogers introduced a novel way to analyze the formation of an image with a set of Young interferograms [4]. Following these ideas, Rhodes [5] showed the interpretation of image-forming process in terms of Young interferograms and in terms of the optical transfer function (OTF) theory using a mask of multiple apertures. First he analyzed objects that are spatially incoherent, and then he extended the analysis to objects whose illumination is partially or fully coherent spatially. On the other hand, Michalski et al. [6] proposed a method to measure the spatial coherence based on the Fourier analysis of the speckle pattern that appears when a diffuser is illuminated with a partially coherent field produced by an incoherent source. In that paper, they explained the principle of the method in considering the speckle pattern as a superposition of many Young interferograms. Another technique to measure the spatial coherence uses a two-dimensional periodic structure (squared mesh) to sample the light field [7]. A lensless imaging process, with an incoherent source, is expressed in terms of the Fourier transform. This technique simultaneously measures the spatial coherence in an array of points over a square mesh.

The last two methods mentioned above assume that the light fields under analysis are produced by spatially incoherent sources. The scope of these methods is limited to light
fields whose spatial coherence is shift invariant. For instance, the modulus of the spatial coherence of the light field produced by an incoherent source synthesized from a laser (TM_{00} mode) and a rotating ground glass \cite{8} is shift invariant, but its phase is shift variant \cite{1}. As more than one pair of points of the light field share the same separation vector, the amplitude of the corresponding Fourier components depends on the redundancy and the phase of the spatial coherence for each pair of points. If the phase of the spatial coherence is shift variant, then different pairs with the same separation vector will have different values for the phase of the spatial coherence. Consequently, as we will show later, in order to measure the spatial coherence, we have to sample the light field in a nonredundant way.

In this paper, we present a criterion to use NRAs to produce a quasi-uniform sampling on the coherence area of the light fields from sources of any type of illumination (incoherent, partially coherent, or fully coherent) and any type of invariance (shift invariant or shift variant). It allows us to obtain surfaces that describe the modulus of the spatial coherence. The method is demonstrated experimentally using two optical sources.

2. THEORY

A. Fourier Spectrum Analysis

Let us suppose that we have the interferogram in the far field generated by a two-dimensional array of \( N \) identical apertures when it is illuminated by a light field of wavelength \( \lambda \). We suppose that the apertures satisfy the following conditions: (a) the diameter of each aperture is much less than the coherence area of the light field, and (b) the amplitude and phase variations are negligible within each aperture. According to the results showed by Mejía and González \cite{2}, the Fourier transform of the interferogram can be written as

\[
\hat{I}(r) = \Lambda(r) \otimes \left[ \sum_{n=1}^{N} I_n \delta(r) + \sum_{n-m=1}^{N-1} \sqrt{I_n I_m} \mu_{nm} \delta(r - (r_n - r_m)) \right] + \mu_{mm} \delta(r + (r_n - r_m)),
\]

where \( r = (\xi, \eta) \) is the position vector on the Fourier transform plane, \( \Lambda(r) \) is the autocorrelation of the function that describes the geometry of the apertures, \( I_n \) is the intensity of the light field in the \( n \)th aperture, \( \mu_{nm} \) is the spatial coherence (complex degree of spatial coherence) of the light field that corresponds to the aperture pair \( (n, m) \), and \( \delta() \) is Dirac’s delta function. The symbol \( \otimes \) represents the convolution operation.

Equation (1) shows that the Fourier transform is a symmetrical and conjugate distribution of peaks with respect to the origin. The shape of the peaks is determined by \( \Lambda(r) \), and the position of the peaks is given by the vector \( (r_n - r_m) \), that is, the separation vector of the aperture pair \( (n, m) \). The height of each peak depends on the multiplication of the factor \( \sqrt{I_n I_m} \) and the spatial coherence \( \mu_{nm} \) that corresponds to the aperture pair \( (n, m) \). If the array of apertures has more than one pair with the same separation vector (redundant array), in the Fourier transform we will have peaks whose height is the sum of the products \( \mu_{nm} \times \sqrt{I_n I_m} \) for different aperture pairs \( (n, m) \) with the same separation vector.

According to the above, it is convenient to define a class of aperture pairs as the set of aperture pairs with the same separation vector \cite{9}; it allows us to identify each peak of the Fourier transform as a class of aperture pairs. Therefore, the \( j \)th peak (that corresponds to the \( j \)th class of aperture pairs) is formed by the sum of all peaks that result from the different aperture pairs with the same separation vector \( d_j \).

If the coherence of the light field is shift invariant, then every pair of the \( j \)th class will have the same spatial coherence, and Eq. (1) can be written as

\[
\hat{I}(r) = \Lambda(r) \otimes \left[ S_0 \delta(r) + \sum_{j=1}^{N} S_j \mu_j (r - d_j) + \mu_j^* \delta(r + d_j) \right],
\]

where \( S_0 = \sum I_n, S_j = \sum \sqrt{I_n I_m}, \) and \( \mu_j = |\mu_j| \exp{i\phi_j} \) is the spatial coherence of the \( j \)th class. Consequently, it is possible to measure the spatial coherence if we know the intensities \( I_n \) of every aperture and the complex amplitude \( c_j = |c_j| \exp{i\phi_j} \) of the peaks on the Fourier transform. In this case, the spatial coherence will be given by \cite{2}

\[
|\mu_j| = \frac{|c_j| S_j}{|c_0| S_0},
\]

where \( |c_0| \) is the modulus of the central peak.

If the coherence of the light field is shift variant, the pairs of the \( j \)th class will have different values for spatial coherence. In other words, in the \( j \)th peak we will have the overlapping of individual peaks with different unknown complex degrees of spatial coherence and, therefore, we cannot measure the spatial coherence from Eq. (3).

As in practice, we do not know \textit{a priori} the type of invariance of the coherence of the light field, we can use Eq. (3) in any case whenever every class of aperture pairs is formed by only one pair; it means that we have to use a mask with a two-dimensional NRA of apertures.

B. Nonredundant Arrays

According to what we said in the last section, the spatial coherence can be measured in any case by using a mask with a NRA of apertures. On the other hand, an optimal measurement of the spatial coherence would be obtained if we have a uniform spatial distribution of peaks in the Fourier transform. Since the location and shape of the peaks in Eq. (2) are determined by the autocorrelation of the NRA of apertures, we will use the autocorrelation function to identify the optimal array of apertures. This has already been carried out in other areas such as coded aperture imaging \cite{10}, aberration compensation using incoherent light \cite{11}, and design of compact nonredundant arrays \cite{12}.

In our application, the NRA of apertures is made by locating the apertures in one intersections of a square grid of size \((m \times n)\) intersections. The autocorrelation will be a distribution of peaks within a square grid of size \((2m - 1) \times (2n - 1)\) intersections. If we normalize the peaks with respect to the autocorrelation of one aperture, the normalized height of the central peak is equal to the total number of apertures, and the height of the remaining peaks is equal to one (because
we have a NRA). In particular, we will use a NRA to generate the larger number of correlation peaks within the square grid of \((2m - 1) \times (2n - 1)\) intersections. It allows us to obtain the most information possible, in order to measure the spatial coherence. In other words, we need to find out the maximum number of apertures that we can locate within the grid of \((m \times n)\) intersections in order to get a NRA of apertures. Methods such as cyclic difference sets [13] or the minimum moment of inertia of Golay [12] for designing NRAs do not always find the maximum number of apertures within the grid of \((m \times n)\) intersections. In this paper, we mention an iterative way to achieve it, but the detailed description is left for a future work.

As the Fourier transform of the interferogram [Eq. (2)] is given by a symmetrical and conjugated distribution of peaks, we select one-half of it to measure the spatial coherence. Therefore, for designing the NRA, we analyze only one-half of the autocorrelation of the NRA.

Let us consider the autocorrelation grid of size \((2m - 1) \times (2n - 1)\) intersections, and let us choose a region of the autocorrelation that contains only the half of the correlation peaks (leaving out the central peak), as shown in Fig. 1. In the selected region we have \(n_{ca} = 2mn - (n + m)\) intersections, which is the maximum number of classes of aperture pairs that we could have for an aperture array within the grid of size \((m \times n)\) intersections. On the other hand, an array of \(k\) apertures generates \(p = k(k - 1)/2\) pairs of apertures. So, if \(p > n_{ca}\), the array will be redundant. It allows us to establish that if \(n_{ca} = k_c(k_c - 1)/2\), then \(k_c\) would be the maximum number of apertures of the NRA of apertures. However, it is found that it is not possible to locate \(k_c\) apertures within the grid of size \((m \times n)\) intersections in a nonredundant way. Therefore, we propose to use an iterative method that decrements \(k_c\) by 1 until we obtain a NRA of apertures; the number of apertures found in this manner will be the maximum number of apertures that we can place within the grid of size \((m \times n)\) in a nonredundant way, and we denote it as \(k_{max}\). Calculating the autocorrelation for all possible spatial distributions of \(k_{max}\) apertures within the grid of size \((m \times n)\) intersections, we determine all NRAs. The value of \(k_c\) is given by

\[
k_c = \text{Int}\left[\frac{1 + \sqrt{1 + 8n_{ca}}}{2}\right].
\]

where \(\text{Int}(x)\) is the integer part of the function of \(x\). Note that with \(k_c\) obtained from Eq. (4), the number of aperture pairs \(p = k_c(k_c - 1)/2\) could be less than \(n_{ca}\). For instance, in a grid of size \((m, n) = (6 \times 6)\) intersections, \(n_{ca} = 2n(n - 1) = 60\), \(k_c = 11\), and \(p = 55\), and after using the iterative method, we find that the maximum number of apertures that generates NRAs is \(k_{max} = 9\). In the upper row of Fig. 2, we show three of the NRAs found with the iterative method for nine apertures within the grid of size \((6 \times 6)\). In the lower row of Fig. 2, we show their autocorrelations; the filled circles represent the autocorrelation peaks (all of the same height), and the central peak is labeled with a larger open circle to point out that this peak is different in height (total number of apertures).

These three cases have the same number of correlation peaks within the grid \((11 \times 11)\), but their spatial distributions are different. The autocorrelation of Fig. 2(a) shows a poor sampling in the upper left and lower right corners. The autocorrelation of Fig. 2(b) shows a better sampling, because there we have a more regular distribution of peaks; the autocorrelation of Fig. 2(c) also shows a regular sampling, but in this case, the number of peaks on the border is less than in Fig. 2(b).

The spatial distribution of the peaks in Fig. 2(b) is the most compact, according to Golay’s criterion [12] that is concerned with the minimum moment of inertia. This criterion allows us to choose an optimal NRA based on a compactibility factor defined as follows: Let \(I_{min}\) be the most compact moment of inertia that we can generate with \(k(k - 1)/2\) peaks in a nonredundant way in the autocorrelation grid, and let \(I_{a}\) be the moment of inertia of the autocorrelation of the NRA obtained with \(k\) apertures; the compactibility factor is \(F = I_{min}/I_{a}\). So, \(F = 1\) means that the NRA has the maximum compactibility. In general \(I_{a} > I_{min}\); therefore, for a set of NRAs with \(k\) apertures, the NRA that generates the most compact autocorrelation will be the one that has the greater \(F\) \((F < 1)\).

In the example of the grid of size \((6 \times 6)\) intersections with \(k = 9\), the number of correlation peaks (leaving out the central peak) is \(2p = 72\). According to Golay, the minimum moment of inertia for these peaks is obtained by placing them in a nonredundant way within the region showed in Fig 3(a). In our example, Fig. 3(b) corresponds to the array with the most compact autocorrelation. On the other hand, a quasi-uniform sampling in the autocorrelation domain implies that a greater

![Fig. 1. Crosshatch pattern shows the region of the autocorrelation that contains only half of the correlation peaks (leaving out the central peak). This region determines the maximum number of apertures that we can have in a NRA.](image)

![Fig. 2. Three NRAs (upper row) and their autocorrelations (lower row). Each NRA is composed by nine apertures within a grid of size \((6 \times 6)\) intersections. Nine is the maximum number of apertures that can be placed in a nonredundant way in these grids. In the autocorrelations, filled circles represent autocorrelation peaks, all of the same height; the central peak, indicated by an open circle, shows that this peak is different in height (total number of apertures).](image)
number of peaks is evenly distributed inside the autocorrelation. As several NRAs with the same number of apertures have the same number of correlation peaks, we are going to choose the NRA with the largest number of correlation peaks within the central region of size $((2m - 3) \times (2n - 3))$. In our example, it corresponds to Fig. 3(b), and the NRA is the one shown in Fig. 2(c). Note that following the last criterion, the autocorrelation of Fig. 2(c) represents a better sampling in the central region compared to Fig. 2(b). In practice, both NRAs sample the autocorrelation domain properly, so either of them is a good selection. The last criterion could be relevant in those cases where the difference in sampling in the central region is significant.

3. EXPERIMENT

In this paper, using Eq. (3), we measure the spatial coherence of two partially coherent and linearly polarized light fields. The first is obtained following the rotating ground glass method for a He-Ne laser (632.8 nm, 5 mW in TM$_{00}$ mode), and the second is the expanded beam of a diode laser (635 nm, 0.6 mW) with a circular cross section. As the results of the rotating ground glass method are well known [8], we carry out the first experiment in order to verify the reliability of our method. Figure 4 shows the setup for measuring spatial coherence. In both cases, the beam is first expanded by the lens L1 (achromatic lens, focal length 14 mm), and then is focused by the lens system L2 (two identical lenses, focal length 450 mm and diameter 100 mm, spaced 50 mm). A mask with the NRA of apertures of Fig. 2(c) is placed just before the first lens of L2. The front focal point of the first lens of L2 is on the back focal point of L1; in this manner, the interference pattern yielded by the NRA is on the back focal plane of the second lens of L2. The diameter of the expanded beam at the mask position is approximately equal to the diameter of the lenses in L2. At the end of the setup, lens L3 (achromatic lens, focal length 20 mm) takes the image of the interference pattern on a CCD sensor (1/4 inch, 768 × 494 pixels, monochrome). It allows us to improve the resolution of the interference fringes and reduce the moiré effect from the CCD lines and the interference fringes (when the spatial period of the fringes is near to the size of CCD pixel). After the interferogram is registered by the CCD, it is numerically processed to obtain $|c_j|$ for every peak of the Fourier transform of the interferogram. These values are taken in the centroid of the peaks. According to Eq. (3b), we also need to measure the intensity in each aperture of the NRA. This is done from the diffraction pattern generated by each aperture [2].

![Fig. 3.](image-url) (a) Region for the minimum moment of inertia (Golay's criterion), (b) region for the nonredundant array with the most compact autocorrelation (in our example).

![Fig. 4.](image-url) Setup for measuring the spatial coherence. Lens L1 expands the light field; lens L2 (two identical lenses) focuses the interferogram generated by a mask with a NRA of apertures (the mask is placed just before the lens L2); lens L3 takes the image of the interference pattern using a CCD sensor. For the first experiment, the rotating ground glass is placed in the back focal plane of L1.

A. Beam Generated with Rotating Ground Glass

With this method, the spatial coherence of the He-Ne laser beam in TM$_{00}$ mode is changed by placing a rotating ground glass at the back focal plane of L1. According to Gori [8], in this plane we will have an incoherent beam. From the van Cittert–Zernike theorem [14], on the mask with the NRA of apertures, the beam is partially coherent, and its spatial coherence is determined from the Fourier transform of the intensity distribution of the beam at the plane of the ground glass. In this case, the complex degree of spatial coherence is Gaussian in type and it is given by

$$
\mu_{mn} = \exp \left[ -i \frac{\pi}{\lambda z} (r_n^2 - r_m^2) \right] \exp \left[ -\frac{(r_n - r_m)^2}{\sigma^2} \right],
$$

where $\omega = \lambda z/\sin \theta$ is the radius of the coherence area (a half-width of the Gaussian function given by Eq. (5)), $\omega_0$ is the radius of the spot at the waist of the focused beam on the ground glass, and $z$ is the distance from the ground glass to the mask with the NRA. The cross section of the expanded beam on the mask with the NRA is now wider than the diameter of lens L2.

![Fig. 5.](image-url) Interferograms generated with the NRA of Fig. 2(c) and their corresponding Fourier spectrums for the laser beam with the rotating ground glass: (a) Interferogram obtained when the center of the aperture grid is on the optical axis, (b) Interferogram obtained when the center of the aperture grid is separated 8 mm from the optical axis, (c) Fourier spectrum of (a), (d) Fourier spectrum of (b).
The spatial period of the grid of the aperture array [Fig. 2(c)] is made 4.0 mm and the radius of the apertures is 0.5 mm. The apertures were drilled with a computer numerical control machine whose step in the $XY$ table is 10 $\mu$m.

Figure 5 shows two interferograms generated with the NRA of Fig. 2(c) and their corresponding Fourier spectrums. The interferogram of Fig. 5(a) is obtained when the center of the aperture grid is on the optical axis, and the interferogram of Fig. 5(b) is obtained when the center of the aperture grid is separated by 8 mm from the optical axis (on the mask plane in the vertical direction). On the other hand, Figs. 5(c) and 5(d) show the Fourier spectrum of the interferograms of Figs. 5(a) and 5(b), respectively. We find that the spatial distribution of the peaks is the same, but the amplitude and phase of the peaks change, since they depend on the intensity in each aperture and the coherence between aperture pairs. Because the amplitude of the central peak is much greater than the rest of peaks, in Figs. 5(c) and 5(d), the central peak is filtered out.

From the amplitude of the peaks of the Fourier spectrum and from the intensity in each aperture, we measure the modulus of the spatial coherence for 36 aperture pairs that result from the NRA. In Figs. 6(a) and 6(b), the dots correspond to the modulus of the spatial coherence measured and the surface corresponds to the interpolation of these data. The coordinates $(\xi_n - \xi_m)$ and $(\eta_n - \eta_m)$ are the components of the separation vector $(r_n - r_m)$ of the aperture pairs. In both cases, the spatial coherence is described by a Gaussian surface, as is expected from Eq. (3). As the modulus of the spatial coherence of this laser beam is shift invariant.

![Fig. 7. Irradiance of the cross section of a diode laser (635 nm, 0.6 mW).](image)
coherence of the beam generated with the rotating ground glass method is shift invariant [Eq. (5)], we also expect that the coherence surfaces will be equal in both experiments. Nevertheless, from Figs. 6(a) and 6(b), the width of the Gaussian surfaces are $2\omega = 10.8 \pm 0.1$ mm and $2\omega = 9.5 \pm 0.1$ mm, respectively. This difference is due to the experimental conditions regarding the He-Ne laser in our laboratory, with two problems: first, the intensity of our laser was variable in time, and second, we registered the intensity of each aperture (diffraction patterns) independently of the interferogram of the NRA. It is clear that if the laser intensity is variable in time, the last measurements introduce relevant errors. A possible solution to this problem is the addition of an optical system in the setup of Fig. 4 that allows us to make the two measurements at the same time (for instance, using a beam splitter and some lenses to project the apertures of the NRA in another CCD camera). In conclusion, we can say that the results in this case correspond to what Eq. (5) describes.

B. Beam of Diode Laser

Figure 7 shows the irradiance of an expanded diode laser beam at the plane of mask with the NRA (Fig. 4). This irradiance differs significantly from the irradiance of the expanded He-Ne laser beam in $\text{TM}_{00}$ mode. Nevertheless, in this case the intensity was steadier in time than the intensity of the He-Ne laser. To measure the spatial coherence, we used the NRA of

![Fig. 8. Interferograms generated with the NRA of Fig. 2(c) and their corresponding Fourier spectra for the diode laser. (a) Interferogram obtained when the center of the aperture grid is on the optical axis, (b) interferogram obtained when the center of the aperture grid is separated by 8 mm from the optical axis, (c) Fourier spectrum of (a), (d) Fourier spectrum of (b).](image)

![Fig. 9. (a) Modulus of the spatial coherence measured from Fig. 8(c); (b) modulus of the spatial coherence measured from Fig. 8(d).](image)
Fig. 2(c), but the diameter of apertures is 0.2 mm. We reduced the diameter in this case in order to maintain the condition that the light field inside each aperture does not change significantly.

Figure 8 shows two interferograms generated with the NRA of Fig. 2(c) and their corresponding Fourier spectra. Again, the interferogram of Fig. 8(a) is obtained when the center of the aperture grid is on the optical axis, the interferogram of Fig. 8(b) is obtained when the center of the aperture grid is separated by 8 mm from the optical axis (on the mask plane in the vertical direction), and Figs. 8(c) and 8(d) are their corresponding Fourier spectra. Similarly, the spatial distribution of the peaks is the same, but the amplitude and phase of the peaks change, and the central peak is filtered out.

Finally, Figs. 9(a) and 9(b) are the modulus of the spatial coherence, where the dots are the measurement of the coherence and the surfaces are the interpolation of the data. Unlike the beam generated with the ground glass, the spatial coherence of the diode laser beam changes noticeably under lateral displacements. The shape of these coherence surfaces indicates that the diode laser beam is determined by the composition of multiple transverse modes [15, 16]. At first glance, the modulus of the spatial coherence of this beam is shift variant, but the differences between these two coherence surfaces can also occur if the composition of the transverse modes changes over time.

In Figs. 9(a) and 9(b), we can see that most of the data for the modulus of the spatial coherence have nonzero values in the border of the area under analysis. If it is necessary to check a larger coherence area, we can change the scale of the NRA or design another NRA that includes more apertures.

4. CONCLUSIONS

In this paper we have shown that with an optimal NRA of apertures, we can effectively sample the coherence domain and, therefore, measure the spatial coherence. The coherence domain is related with the Fourier spectrum of the interferogram generated by the NRA when it is illuminated by the light field under analysis. The advantage of our method in comparison to the Young interferometry is that we can measure the entire coherence area with only one interferogram and with a simple optical setup. If the NRA is composed of N apertures, we can measure the spatial coherence for \( N(N - 1)/2 \) samples, and from these data we can obtain a coherence surface by interpolation. To obtain the same information by performing \( N(N - 1)/2 \) Young experiments, i.e., \( N(N - 1)/2 \) masks of two apertures, would require a considerable period of time. Another advantage of our method is that by using a mask with a NRA of apertures for two different transversal positions, we can determine if the modulus of the spatial coherence is shift variant or invariant. This method can also use to analyze the composition of the transverse modes in laser cavities.

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