Generating electromagnetic dark and antidark partially coherent sources

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Abstract
We present two methods to generate an electromagnetic dark and antidark partially coherent source. The first generalizes a recently published scalar approach by representing the stochastic electric field vector components as sums of randomly weighted, randomly tilted plane waves. The second method expands the field’s vector components in series of randomly weighted dark and antidark coherent modes. The statistical moments of the random weights—plane waves in the former method, coherent modes in the latter—are found by comparing the resulting means and covariances to those of the desired electromagnetic dark and antidark source. We validate both methods by simulating the generation of an electromagnetic dark or antidark source and comparing the simulated results to the corresponding theoretical predictions. We find that both methods converge to the theoretical, ensemble-averaged (long-time-averaged) statistics within roughly 500 random field instances. The methods presented in this paper will find use in applications that utilize dark and antidark beams, e.g. atomic optics and optical trapping.

1. Introduction
Dark or antidark (DAD) beams are a type of dispersion-free or diffraction-free wave that has a dark or bright notch in on-axis intensity. These waves were first discovered as solitons in optical fibers [1, 2]. Ponomarenko et al. [3] showed that similar DAD waves can exist in linear media, granted the optical field is partially coherent.

Since that time, scalar DAD partially coherent sources (PCSs) have been experimentally realized using the source’s coherent-mode representation [3, 4] and by passing a $J_0$-Bessel correlated PCS [5–7] through a wavefront-folding interferometer [8, 9]. In another recent paper, the authors showed that DAD beams could be realized from stochastic optical fields that are the weighted sums of randomly tilted plane waves [10].

Although a generalized, electromagnetic version of DAD beams was formulated shortly after Ponomarenko et al.’s original paper [11], to our knowledge, an electromagnetic DAD PCS has never been synthesized. [11] is very general and describes a whole class of diffraction-free, electromagnetic PCSs composed of uncorrelated Bessel beams, of which vector DAD beams are one example.

Here, we generate an example electromagnetic DAD beam discussed in [11] in two ways. The first extends the scalar approach presented in [10], where the vector components of the electric field are formed from the randomly weighted sums of randomly tilted plane waves. In the second approach, we expand the stochastic vector components of the electric field in sums of randomly weighted DAD coherent modes. In both methods, we find the statistics of the random weights by taking the auto- and cross-correlations of the field’s vector components and comparing those correlations to the corresponding electromagnetic DAD source cross-spectral density (CSD) matrix elements.

In the next section, we present the statistical optics theory necessary to understand and implement both approaches. We then simulate the generation of an electromagnetic DAD PCS using both methods and compare the results to the corresponding theoretical expressions. Lastly, we conclude our work with a brief summary.
2. Theory

We begin with the electromagnetic DAD source CSD matrix $W$ given in equations (41) and (42) of [11]:

$$
W_{\alpha\beta}(\rho_1, \rho_2) = \sum_{n=-\infty}^{\infty} \lambda_n \Phi_n(\rho_1) \Phi_n^*(\rho_2),
$$

$$
W_{\gamma\gamma}(\rho_1, \rho_2) = a \sum_{n=-\infty}^{\infty} \Phi_n(\rho_1) \Phi_n^*(\rho_2),
$$

where $\alpha = x, y, \rho = \hat{x}x + \hat{y}y$, $J_0(x)$ is a zeroth-order Bessel function of the first kind, $\kappa$ is a real constant and related to the coherence width of the source, $\chi$ is a real constant subject to the constraint $|\chi| < 1$, and $a$ is a complex constant such that $|a| < 1 - |\chi|$. The coherent-mode representation of the above electromagnetic DAD PCS is

$$
W_{\alpha\beta}(\rho_1, \rho_2) = \sum_{n=-\infty}^{\infty} \lambda_n \Phi_n(\rho_1) \Phi_n^*(\rho_2),
$$

where the eigenvalues $\lambda_n$ and eigenfunctions $\Phi_n$ are

$$
\lambda_n = 1 + \chi (-1)^n
$$

$$
\Phi_n(\rho) = J_n(\kappa \rho) \exp(jn\phi).
$$

The propagation and polarization characteristics of these beams can be found in [3, 11].

2.1. Method 1: genuine CSD function criterion

In [10], using the genuine CSD function criterion [12, 13], the author showed that a scalar DAD source could be produced by summing many independent realizations of

$$
U(\rho) = \sqrt{\frac{1 + \sqrt{1 - \chi^2}}{2}} \left[ \exp(j\kappa \cdot \rho) + \frac{\chi}{1 + \sqrt{1 - \chi^2}} \exp(-j\kappa \cdot \rho) \right],
$$

where $\kappa = \hat{x}x + \hat{y}y$ is a random vector. The radius $\rho$ and angle $\theta$ are drawn from the following joint probability density (PDF) function:

$$
p(\rho) = p(\theta) p(\psi) = \frac{1}{2\pi} \delta(\psi - 1),
$$

where $\delta(x)$ is the Dirac delta function.

To extend this method to produce the electromagnetic DAD source in equation (1), we let the electric field be

$$
E(\rho) = \hat{x}E_x(\rho) + \hat{y}E_y(\rho),
$$

where the stochastic vector components are

$$
E_{\alpha}(\rho) = b_{\alpha} \exp(j\kappa \cdot \rho) + c_{\alpha} \exp(-j\kappa \cdot \rho).
$$

In equation (7), the $b_{\alpha}$ and $c_{\alpha}$ are complex random numbers. This stands in contrast to the scalar case, where the plane wave coefficients are deterministic [see equation (4)].

Taking the auto-correlation of equation (7) and assuming that $b_{\alpha}$ and $c_{\alpha}$ are statistically independent of $\psi$ yields

$$
W_{\alpha\alpha}(\rho_1, \rho_2) = \langle b_\alpha^* b_\alpha \rangle \langle \exp(j\kappa \cdot \rho_1) \rangle + \langle c_\alpha^* c_\alpha \rangle \langle \exp(-j\kappa \cdot \rho_1) \rangle
$$

$$
+ \langle b_\alpha^* c_\alpha \rangle \langle \exp(j\kappa \cdot \rho_1) \rangle + \langle c_\alpha^* b_\alpha \rangle \langle \exp(-j\kappa \cdot \rho_1) \rangle,
$$

where $\rho_{\alpha,\beta} = \rho_1 \pm \rho_2$. The moments containing the complex exponentials are equivalent to the joint characteristic functions of $\psi$. Using the joint PDF in equation (5), these moments are easy to compute, and equation (8) simplifies to

$$
W_{\alpha\alpha}(\rho_1, \rho_2) = \langle \langle b_\alpha^* b_\alpha \rangle + \langle c_\alpha^* c_\alpha \rangle \rangle J_0(\kappa \rho_{\alpha,\beta}) + 2 \text{Re} \langle \langle b_\alpha c_\alpha^* \rangle \rangle J_0(\kappa \rho_{\alpha,\beta}).
$$

Comparing equations (1) and (9) and expanding $b_{\alpha}$ and $c_{\alpha}$ into real and imaginary parts reveals the following equalities:

$$
\langle (b_\alpha^* b_\alpha) \rangle + \langle (b_\alpha^* c_\alpha) \rangle + \langle (c_\alpha^* b_\alpha) \rangle + \langle (c_\alpha^* c_\alpha) \rangle = 1
$$

$$
\langle b_\alpha^* b_\alpha \rangle + \langle b_\alpha^* c_\alpha \rangle + \langle b_\alpha c_\alpha^* \rangle + \langle c_\alpha^* c_\alpha \rangle = \chi / 2.
$$
For simplicity, we let the variances and covariances on the left-hand sides of equation (10) be equal producing
\[
\begin{align*}
\langle (b_i')^2 \rangle &= \langle (b_i'')^2 \rangle = \langle (c_i')^2 \rangle = \langle (c_i'')^2 \rangle = 1/4 \\
\langle b_i' c_i' \rangle &= \langle b_i'' c_i'' \rangle = \chi/4.
\end{align*}
\] (11)

Referring back to equation (7), we now take the cross-correlation of \(E_x\) and \(E_y\) yielding
\[
W_{xy}(\rho_1, \rho_2) = \langle b_x b_y^* \rangle \exp \left( j k \nu \cdot \rho_1 \right) + \langle c_x c_y^* \rangle \exp \left( -j k \nu \cdot \rho_2 \right)
+ \langle b_x c_y^* \rangle \exp \left( j k \nu \cdot \rho_1 \right) + \langle b_y c_x^* \rangle \exp \left( -j k \nu \cdot \rho_2 \right)
= \langle (b_x b_y^* + c_x c_y^*) \rangle h_0(\kappa \rho_1) + \langle (b_x c_y^* + b_y c_x^*) \rangle h_0(\kappa \rho_2).
\] (12)

Comparing the above \(W_{xy}\) to the desired one in equation (1) reveals
\[
\begin{align*}
\langle b_x b_y^* \rangle + \langle c_x c_y^* \rangle + \langle c_x' c_y^* \rangle + \langle c_x' c_y^* \rangle &= a' \\
\langle b_x b_y^* \rangle - \langle c_x c_y^* \rangle + \langle c_x' c_y^* \rangle - \langle c_x' c_y^* \rangle &= a' \\
\langle b_x c_y^* \rangle + \langle b_y c_x^* \rangle + \langle c_x b_y^* \rangle + \langle c_x b_y^* \rangle &= 0 \\
\langle b_x c_y^* \rangle - \langle b_y c_x^* \rangle + \langle c_x b_y^* \rangle - \langle c_x b_y^* \rangle &= 0.
\end{align*}
\] (13)

For simplicity, we let
\[
\begin{align*}
\langle b_x b_y^* \rangle &= \langle b_x b_y^* \rangle = \langle c_x c_y^* \rangle = \langle c_x c_y^* \rangle = a'/4 \\
\langle b_x c_y^* \rangle &= \langle c_x c_y^* \rangle = \langle c_x c_y^* \rangle = \langle c_x c_y^* \rangle = a'/4 \\
\langle b_x c_y^* \rangle &= \langle b_x c_y^* \rangle = \langle c_x b_y^* \rangle = \langle c_x b_y^* \rangle = 0 \\
\langle b_x c_y^* \rangle &= \langle b_x c_y^* \rangle = \langle c_x b_y^* \rangle = \langle c_x b_y^* \rangle = 0.
\end{align*}
\] (14)

to complete the derivation.

Note that we chose the second moment values in equations (11) and (14) solely for convenience. Any values that satisfy the linear constraint equations in equations (10) and (13), as well as the conditions on \(\chi\) and \(a'\) specified below equation (1), are valid.

In summary, an electromagnetic DAD PCS with a CSD matrix given in equation (1) can be produced by incoherently summing stochastic vector fields, whose components take the form of equation (7). The radius \(r\) and angle \(\theta\) of the random vector \(\mathbf{r}\) are drawn from the joint PDF given in equation (5). Lastly, the random complex coefficients \(b_i\) and \(c_i\) are zero mean and have a covariance matrix \(\mathbf{K}\) equal to
\[
\mathbf{K} = \left[\begin{array}{ccc}
\langle b_x \rangle & \langle b_x' \rangle & \langle b_x'' \rangle \\
\langle c_x \rangle & \langle c_x' \rangle & \langle c_x'' \rangle \\
\end{array}\right]
= \frac{1}{4} \begin{pmatrix}
1 & 0 & \chi & 0 & a' & -a' & 0 & 0 \\
0 & 1 & 0 & a' & a' & a' & 0 & 0 \\
\chi & 0 & 1 & 0 & 0 & a' & -a' & 0 \\
0 & \chi & 0 & 1 & 0 & a' & a' & 0 \\
0 & 0 & a' & a' & 0 & 0 & 1 & 0 \\
-1 & 0 & 0 & 0 & 0 & 1 & 0 & \chi \\
0 & 0 & -a' & a' & \chi & 0 & 1 & 0 \\
0 & 0 & -a' & -a' & 0 & \chi & 0 & 1
\end{pmatrix}.
\] (15)

The statistical distributions of \(b_i\) and \(c_i\) are irrelevant as long as the first and second moments are equal to those specified above. Because it is easy to generate correlated normal random numbers, we recommend letting \(b_i\) and \(c_i\) be jointly Gaussian distributed.

2.2. Method 2: coherent modes

Here, we expand \(E_x\) and \(E_y\) in series of DAD coherent modes, where the coherent mode weights are complex random numbers.

We note that a similar expansion was first employed by Kim and Wolf [14], although for a different purpose. By treating the Hermitian CSD matrix \(\mathbf{W}\) diagonal elements \((W_{xx} \text{ and } W_{yy})\) as scalar PCSs and expanding each in two distinct sets of orthogonal coherent modes, Kim and Wolf were able to derive a bi-modal (double series) expansion for the non-Hermitian off-diagonal elements. This procedure, requiring the solutions of two uncoupled integral equations to find the modes of \(W_{xx}\) and \(W_{yy}\), is considerably simpler than the traditional approach, which requires solving a set of coupled integral equations. Of course, the price paid for this simplicity is the double series representation for \(W_{xy}\).

In our case however, because \(W_{xx}\) and \(W_{yy}\) have the same coherent modes [see equation (2)], this approach turns out to be quite convenient. We begin by expanding \(E_x\) and \(E_y\) as
\[ E_x(\rho) = \sum_{n=-\infty}^{\infty} b_n \Phi_n(\rho) \]
\[ E_y(\rho) = \sum_{n=-\infty}^{\infty} c_n \Phi_n(\rho), \]

where \( \Phi_n \) is defined in equation (3) and \( b_n \) and \( c_n \) are random complex numbers drawn from some arbitrary distribution.

It is important to emphasize that this approach is fundamentally different to using coherent modes to generate scalar PCSs. In the latter, the deterministic field consists of a single weighted mode. The scalar PCS is formed by summing the weighted modes incoherently typically at the detector \([4, 15, 16]\). Here, a stochastic field realization is formed from the randomly weighted, coherent addition of many modes. The electromagnetic PCS is formed by incoherently summing many statistically independent vector field realizations.

Taking the auto-correlation of equation (16) yields
\[ W_{xx}(\rho_1, \rho_2) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \langle b_n b_{m}^* \rangle \Phi_n(\rho_1) \Phi_m^*(\rho_2), \]

with a similar expression for \( W_{yy} \). Comparing this expression (and the \( W_{xy} \) expression) to the coherent-mode representation in equation (2) reveals that
\[ \langle b_n b_{m}^* \rangle = \langle c_n c_{m}^* \rangle = \lambda_n \delta_{nm}, \]

where \( \delta_{nm} \) is the Kronecker delta function.

We now turn our attention to the off-diagonal elements. Taking the cross-correlation of the vector components in equation (16) produces
\[ W_{xy}(\rho_1, \rho_2) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \langle b_n c_{m}^* \rangle \Phi_n(\rho_1) \Phi_m^*(\rho_2). \]

Comparing this expression to \( W_{xy} \) in equation (2) reveals the following:
\[ \langle b_n c_{m}^* \rangle = \alpha \delta_{nm}. \]

We note that because of the Kronecker delta functions in equations (18) and (20), there is no coupling between different index modes in equation (16). Taking this into account and expanding \( b_n \) and \( c_n \) in real and imaginary parts produces
\[ \langle (b_n^x)^2 \rangle + \langle (b_n^y)^2 \rangle = \lambda_n \]
\[ \langle (c_n^x)^2 \rangle + \langle (c_n^y)^2 \rangle = \lambda_n \]
\[ \langle b_n^x c_n^x \rangle + \langle b_n^y c_n^y \rangle = \alpha^2 \]
\[ \langle b_n^x c_n^y \rangle - \langle b_n^y c_n^x \rangle = \alpha i. \]

Again, for simplicity, we let
\[ \langle (b_n^x)^2 \rangle = \langle (b_n^y)^2 \rangle = \lambda_n / 2 \]
\[ \langle (c_n^x)^2 \rangle = \langle (c_n^y)^2 \rangle = \lambda_n / 2 \]
\[ \langle b_n^x c_n^x \rangle = \langle b_n^y c_n^y \rangle = \alpha^2 / 2 \]
\[ \langle b_n^x c_n^y \rangle = \langle b_n^y c_n^x \rangle = \alpha i / 2. \]

Like in method 1, the values specified for the second moments in equation (22) are chosen for convenience. Any values that satisfy the linear constraint equations in equation (21) and the \( \chi \) and \( \alpha \) conditions stated above are valid.

Summarizing this method, an electromagnetic DAD PCS with a CSD matrix given in equation (1) can be generated by incoherently summing many realizations of the \( E_x \) and \( E_y \) given in equation (16). The means and covariances of \( b_n \) and \( c_n \) are zero and
\[ K = \begin{bmatrix} b_n & b_n^* \\ c_n & c_n^* \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \lambda_n & 0 & \alpha^2 & -\alpha^2 \\ 0 & \lambda_n & \alpha^2 & \alpha^2 \\ \alpha^2 & \alpha^2 & \lambda_n & 0 \\ -\alpha^2 & \alpha^2 & 0 & \lambda_n \end{bmatrix}. \]

Like method 1, the distributions of \( b_n \) and \( c_n \) are irrelevant as long as the means are zero and the covariance matrix equals equation (23). Again, Gaussian random numbers are a very convenient choice.
3. Simulation

In this section, we simulate the generation of an electromagnetic DAD PCS with \( \chi = -0.8, a = 0.2 \exp(j\pi/4) \), and \( \kappa = 1 \) unit \(^{-1}\) using both methods derived in section 2. In the field expressions for methods 1 and 2 [equations (7) and (16), respectively], \( \kappa \) (recall that \( \kappa \) is related to the coherence width of the source) scales the physical vector \( \rho \). Therefore, the features of electromagnetic DAD beams shown in the results below are simply magnified (or demagnified) by varying \( \kappa \).

As we show in the accompanying MATLAB\textsuperscript{®} simulation code, we used square computational grids that were \( L = 40 \) units in width and 512 points on a side. For both methods, we generated 50,000 stochastic field realizations to compute the spectral densities \( S(\rho) = W_{xx}(\rho, \rho) + W_{yy}(\rho, \rho) \) and two-dimensional planar cuts of the CSD matrix \( W(x_0, 0, x_0, 0) \). Prior scalar DAD source work showed that 50–60 modes were sufficient to accurately represent the PCS \([3, 4]\). To create high-fidelity stochastic fields, we used 121 modes \( (n = -60, -59, \ldots, 60) \) in the expansions in equation (16).

Figure 1 shows stochastic electromagnetic DAD field realizations (magnitudes and phases of \( E_x \) and \( E_y \)) for both methods 1 and 2. Recall that for method 1, a DAD stochastic vector component realization is the sum of randomly tilted ‘forward’ [positive complex exponential in equation (7)] and ‘reverse’ [negative complex

![Field realizations for methods 1 and 2](image)

**Figure 1.** Field realizations for methods 1 and 2 [equations (7) and (16), respectively]—(a) method 1 \( |E_x| \) (top) and \( \arg(E_x) \) (bottom), (b) method 2 \( |E_x| \) (top) and \( \arg(E_x) \) (bottom), (c) method 1 \( |E_y| \) (top) and \( \arg(E_y) \) (bottom), and (d) method 2 \( |E_y| \) (top) and \( \arg(E_y) \) (bottom).
exponential in equation (7) plane waves. Like the tilt (or direction), the amplitudes of the forward and reverse plane waves are also random.

Note that this is precisely the field that is shown in figures 1(a) and (c). The grating-like, or standing-wave behaviors in figures 1(a) and (c) are due to the coherent addition (interference) of the forward and reverse plane waves in $E_x$ and $E_y$. The interference patterns in $E_x$ and $E_y$ are oriented in the same direction. This will always be the case, as this is required to produce the CSD matrix elements in equation (1); however, the ‘grating’ direction will change from field realization to field realization. Likewise, the amplitudes of $E_x$ and $E_y$, being random, will change from field realization to field realization.

For method 2, a DAD stochastic vector component realization is the sum of randomly weighted DAD coherent modes, or equivalently, Bessel beams. It is the coherent sums of these randomly weighted Bessel beams that is responsible for the patterns in figures 1(b) and (d). The branch points (phase vortices) evident in the lower images of figures 1(b) and (d) occur at points of perfect destructive interference (amplitude or intensity nulls). These branch point locations and more generally, the interference patterns themselves, will change with the random weights $b_n$ and $c_n$ in equation (16) from field realization to field realization.

Figures 2 and 3 show the spectral density $S$ and CSD matrix $W(x, 0, y, 0)$ results, respectively. In figures 2(a), (b), and (c) show the theoretical, method 1, and method 2 $S$. All are plotted using the same color scale defined by the color bar to the right of figure 2(c). Figure 2(d) shows the $y = 0$ slices $S(x, 0)$ through (a), (b), and (c) on the same plot for comparison, and (e) shows the two-dimensional correlation coefficients $C$ for the methods 1 and 2 $S$ computed against $S$ theory versus trial number. The inset in figure 2(e) shows $C$ from trials 1,000–50,000.

$$C = \frac{\sum_{k=1}^{N^2}(S_{\text{sim}}[k] - \bar{S}_{\text{sim}})(S_{\text{th}}[k] - \bar{S}_{\text{th}})}{\sqrt{\sum_{k=1}^{N^2}(S_{\text{sim}}[k] - \bar{S}_{\text{sim}})^2} \sqrt{\sum_{k=1}^{N^2}(S_{\text{th}}[k] - \bar{S}_{\text{th}})^2}}, \quad (24)$$
where \( N^2 = 512^2 \) was the total number of pixels in an image, \( \bar{S} \) was the average value of the spectral density, and \( k \) was a discrete pixel index.

Figure 3 is organized like the \( 2 \times 2 \) CSD matrix \( \mathbf{W} \). Each \( \mathbf{W} \) element consists of 6 images arranged in 2 rows and 3 columns and is labeled for the reader’s convenience. The theoretical, method 1, and method 2 \( \mathbf{W}_{xx} \) results—real (top) and imaginary (bottom) parts of \( \mathbf{W}_{xx} \) (a) theory, (b) method 1, (c) method 2; real (top) and imaginary (bottom) parts of \( \mathbf{W}_{xy} \) (d) theory, (e) method 1, (f) method 2; real (top) and imaginary (bottom) parts of \( \mathbf{W}_{yx} \) (g) theory, (h) method 1, (i) method 2; and real (top) and imaginary (bottom) parts of \( \mathbf{W}_{yy} \) (j) theory, (k) method 1, (l) method 2.

The agreement between theory and simulation for both methods is excellent. The results in figures 2 and 3 show that both methods produce an electromagnetic DAD source with the proper shape and correlation (coherence) properties, respectively. In addition, figure 2(e) shows that both approaches converge to the theoretical, or desired source after integrating 500 stochastic field realizations. We note that electromagnetic DAD PCSs radiate diffraction-free beams and therefore, the shapes of the spectral density and CSD matrix elements pictured in figures 2 and 3 do not change upon propagation.

4. Conclusion

In this paper, we presented two methods to produce an electromagnetic dark and antidark (DAD) partially coherent source (PCS). The first, extending a recently published scalar DAD PCS method [10], represented the field’s vector components, \( E_x \) and \( E_y \), as sums of randomly weighted, randomly tilted plane waves. The second expanded \( E_x \) and \( E_y \) in series of randomly weighted DAD coherent modes. By comparing the stochastic fields’ auto- and cross-correlations to the theoretical DAD source CSD matrix, we were able to generate realizations of the random weights using a multivariate Gaussian random number generator.

We simulated the generation of an electromagnetic DAD source using both methods and validated our analysis by comparing the simulated spectral densities and CSD matrices to their theoretical counterparts. The agreement between simulation and theory was excellent. In addition, we found that both approaches converged to the theoretical moments within 500 stochastic field realizations. This finding will be useful to those who implement these methods for a specific application.
Lastly, we note that both methods presented in this paper can be implemented on vector beam generators that utilize one or two spatial light modulators [17–20]. Our work will find use in applications germane to DAD beams, e.g. atomic optics and optical trapping.

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