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Construction of spatial-coherence spectral filters using a Fourier-achromat system

Hem C. Kandpal *, Ranjana Mehrotra

Optical Radiation Standards, National Physical Laboratory, New Delhi 110 012, India

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Abstract

Theoretical investigations made not long ago regarding the construction of spatial-coherence spectral filters (SCSFs) are rendered into experiments by designing and fabricating a Fourier-achromat experimental setup analyzed in the theoretical studies. It is shown that the phenomenon of spectral shift due to spatial coherence also known as the Wolf effect can be exploited to make special types of low-pass and band-pass spectral filters with special spectral characteristics that are not shown by the conventional filters. A Fourier-achromat is employed to construct the SCSFs. The experimental results within the experimental limitations and measurement uncertainty agree well with the theory. These filters might find applications in (i) astronomy (in the search of particular spectral lines) (ii) developing spectrum-selective optical interconnects or (iii) in cryptography.

Keywords: Spatial-coherence spectral filters; Fourier-achromat; Spatial coherence; Coherence-induced spectral changes

1. Introduction

It is now well known that the spectrum of partially coherent source may differ from the spectrum of the source, even in free-space propagation and that the far zone spectrum of the radiation depends not only on the spectrum of the source but also on the correlation properties of the source. This phenomenon is termed as the correlation-induced spectral changes and is known as the Wolf effect [1]. Various groups [2–7] have verified this phenomenon. Many applications of this effect have also been shown [8].

Not long ago Wolf et al. [9] and Shirai et al. [10] showed theoretically that the phenomenon of coherence-induced spectral changes could be used for constructing novel types of spectral filters called the spatial-coherence spectral filters (SCSFs), which have several properties that are not achievable with the conventional filters. Such filters may change the spectral degree of coherence of the transmitted light and consequently the spectrum of the field is also modified. In these studies they have analyzed theoretically the Fourier-achromat (FA) [9] and the Indebetouw systems [10] in detail and have shown how these systems could be modified to produce spatial-coherence spectral filters.

In this paper, we describe the first experimental verification of the theoretical findings for the construction of spatial-coherence spectral filters using the phenomenon of correlation-induced spectral changes. It is shown for the first time that the Fourier-achromat system [2,3] used for producing correlation-induced spectral shifts can also be used for producing SCSFs. These studies might find many applications.

1.1. Construction of SCSFs

Experimental setup was constructed in accordance with the theoretical inputs already available for the FA systems. Fourier-achromat as per design of Brophy [11] was constructed by Mr. C.S. Dahiya of M/s. Optiregion, New Delhi, India. This experimental setup is shown in Fig. 1.

* Corresponding author.
E-mail address: hckandpal@mail.nplindia.ernet.in (H.C. Kandpal).

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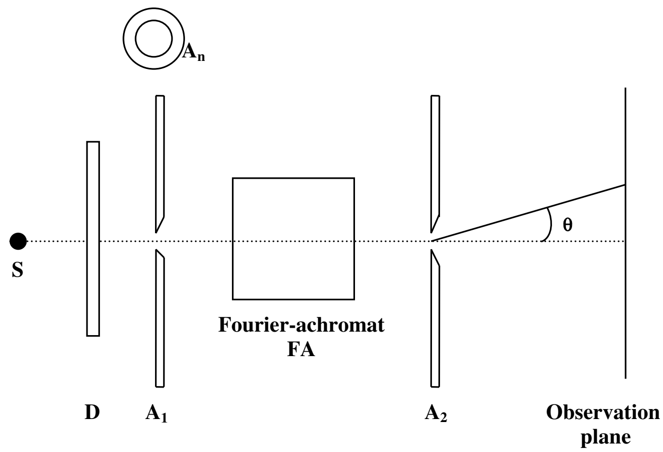

Fig. 1. Experimental setup for observation of spatial-coherence spectral filters using a Fourier-achromat. S is a tungsten halogen lamp, A_1, A_2 and A_3 are the circular apertures, A_n is the annular aperture (which replaces circular aperture A_1, for producing no-uniform band pass filter), FA is the Fourier-achromat.

1.2. Theoretical background for achieving SCSFs with Fourier-achromat system

To achieve SCSFs, the theories put forward by Wolf et al. [9] for the realization of the filters were made the basis of the experimental study. Let us consider a planar quasi-homogeneous source, which occupies a finite domain in the source plane and radiates into the positive half space of the plane containing the source. It has been shown theoretically that if $S^{(0)}(\boldsymbol{\rho},\omega)$ is the spectral density at a point represented by position vector $\boldsymbol{\rho}$ in the source plane and if $\mu^{(0)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega)$ be the spectral degree of coherence, which depends on $\boldsymbol{\rho}_1$ and $\boldsymbol{\rho}_2$ only within the source through the difference $\boldsymbol{\rho}'=\boldsymbol{\rho}_2-\boldsymbol{\rho}_1$ and if we define $\mu^{(0)}(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,\omega)=g^{(0)}(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1,\omega)$, the spectral-density of the field generated by such a source in the far zone [9] is given by

$$S^{(\infty)}(r\mathbf{s},\omega)=\left(\frac{2\pi k}{r}\right)^2\widetilde{S}^{(0)}(0,\omega)\tilde{g}^{(0)}(k\mathbf{s}_\perp,\omega)\times\cos^2\theta, \qquad (1)$$

where $k=\frac{\omega}{c}$, and c is the speed of light. Refer to Wolf et al. [9] for details and notations. Eq. (1) can also be expressed as

$$S^{(\infty)}(r\mathbf{s},\omega)=F(\omega,r,\mathbf{s})S^{(0)}(\omega), \qquad (2)$$

where

$$F(\omega;r,\mathbf{s})=\frac{A\omega^2}{c^2r^2}\tilde{g}^{(0)}(k\mathbf{s}_\perp,\omega)\times\cos^2\theta. \qquad (3)$$

$F(\omega;r,\mathbf{s})$ is the linear filter function changing the spectrum of the source $S^{(0)}(\omega)$ (which is supposed to be the same at every source point) into different spectrum $S^{(\infty)}(r\mathbf{s},\omega)$ of the radiated field in the far zone. Therefore, $F(\omega;r,\mathbf{s})$ is referred to as the filter function. Eq. (3) shows that this function depends on the two dimensional spatial Fourier transform $\tilde{g}^{(0)}(k\mathbf{s}_\perp,\omega)$ of the spectral degree of coherence of the source and the direction of observation via the factor $\cos^2\theta$ and the argument $\mathbf{s}_\perp$ of $\tilde{g}^{(0)}(k\mathbf{s}_\perp,\omega)$, A is the area of the source. It has been shown that non-uniform low-pass filters can be produced by synthesizing a secondary source whose spectral degree of coherence is a 'Besinc' function, namely

$$g^{(0)}(\rho,\omega)=\frac{2J_1(k_1\rho')}{(k_1\rho')}, \qquad (4)$$

where J_1 is the Bessel function of first kind and first order and k_1 is a positive constant, with the dimension of inverse length. The filter functions that have been obtained in the theoretical calculations are as follows [9]:

$$\begin{aligned}
&F(\omega;r,s)=\frac{A}{\pi r^2}\left(\frac{\omega}{\omega_1}\right)^2\times\cos^2\theta \quad \text{when } \omega<\frac{\omega_1}{\sin\theta},\\
&F(\omega;r,s)=\frac{A}{2\pi r^2}\left(\frac{\omega}{\omega_1}\right)^2\times\cos^2\theta \quad \text{when } \omega=\frac{\omega_1}{\sin\theta},\\
&F(\omega;r,s)=0 \quad \text{when } \omega>\frac{\omega_1}{\sin\theta}.
\end{aligned} \qquad (5)$$

Non-uniform bandpass filter can be obtained by constructing a secondary source whose spectral degree of coherence is given by the expression [9]

$$g^{(0)}(\boldsymbol{\rho},\omega)=\frac{1}{k_2^2-k_1^2}\left[k_2^2\left(\frac{2J_1(k_2\rho')}{k_2\rho'}\right)-k_1^2\left(\frac{2J_1(k_1\rho')}{k_1\rho'}\right)\right], \qquad (6)$$

where k_1 and k_2 are positive constants and $k_2>k_1$. The filter functions in this case are given as [9]

$$\begin{aligned}
&F(\omega;r,s)=0 \quad \text{when } \omega<\frac{\omega_1}{\sin\theta},\\
&F(\omega;r,s)=\frac{A}{\pi r^2}\frac{\omega^2}{\omega_2^2-\omega_1^2}\times\cos^2\theta\\
&\quad \text{when } \frac{\omega_1}{\sin\theta}<\omega<\frac{\omega_2}{\sin\theta},\\
&F(\omega;r,s)=0 \quad \text{when } \omega>\frac{\omega_1}{\sin\theta},
\end{aligned} \qquad (7)$$

where $\omega_1=k_1c$ and $\omega_2=k_2c$ and

$$\begin{aligned}
&F(\omega;r,s)=\frac{A}{2\pi r^2}\frac{\omega^2}{\omega_2^2-\omega_1^2}\times\cos^2\theta,\\
&\quad \text{when } \omega=\frac{\omega_1}{\sin\theta} \quad \text{or} \quad \omega=\frac{\omega_2}{\sin\theta}.
\end{aligned} \qquad (8)$$

One has a linear filter action, which acts as a non-uniform bandpass filter with the pass band

$$\frac{\omega_1}{\sin\theta}\leqslant\omega\leqslant\frac{\omega_2}{\sin\theta}. \qquad (9)$$

The cut-off frequencies

$$\omega_{c1}=\frac{\omega_1}{\sin\theta} \quad \text{and} \quad \omega_{c2}=\frac{\omega_2}{\sin\theta} \qquad (10)$$

depend on the observation angle θ.

2. Experimental setup and results

To study the construction of SCSFs using a Fourier-achromat, we created a polychromatic secondary source