Design framework for a spectral mask for a plenoptic camera

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ABSTRACT
Plenoptic cameras are designed to capture different combinations of light rays from a scene, sampling its lightfield. Such camera designs capturing directional ray information enable applications such as digital refocusing, rotation, or depth estimation. Only few address capturing spectral information of the scene. It has been demonstrated that by modifying a plenoptic camera with a filter array containing different spectral filters inserted in the pupil plane of the main lens, sampling of the spectral dimension of the plenoptic function is performed. As a result, the plenoptic camera is turned into a single-snapshot multispectral imaging system that trades-off spatial with spectral information captured with a single sensor. Little work has been performed so far on analyzing diffraction effects and aberrations of the optical system on the performance of the spectral imager. In this paper we demonstrate simulation of a spectrally-coded plenoptic camera optical system via wave propagation analysis, evaluate quality of the spectral measurements captured at the detector plane, and demonstrate opportunities for optimization of the spectral mask for a few sample applications.

Keywords: Plenoptic camera, spectral filters, filter layout, radial partition, spectral crosstalk, quality metric, optimization.

1. INTRODUCTION
Plenoptic cameras are designed to capture different combinations of light rays from a scene, sampling its lightfield. Whereas most of these camera designs capture directional information of rays and target applications such as digital refocusing, rotation, or depth estimation, only few address capturing spectral information of the scene. Authors in\textsuperscript{1,2} modify a plenoptic camera with a filter array inserted in the optical path of the main lens, containing different spectral and polarization filters. With this modification, sampling of the spectral dimension of the plenoptic function is performed. Light rays originating from one point source enter the pupil plane at different locations, therefore, passing through different filters. The microlens array mounted close to the sensor images the pupil plane onto the sensor, measuring spectral scene information as it is passing through the pupil plane (Fig. 1). As a result, the plenoptic camera is turned into a single-snapshot multispectral imaging system that trades-off spatial with spectral information captured with a single sensor. It does not require image registration of spectral bands and enables faster data acquisition in a video mode.

The spectral filter mask, inserted into the main lens, introduces diffraction effects in addition to those caused by the light passing through main lens and microlenses. Further distortions into the optical path are introduced due to the filter-dependent chromatic aberration that may introduce out of focus blur at the microlens and sensor plane. Chromatic aberration can be overcome to some extent by using an achromatic design for the main lens. It is difficult, however, to manufacture achromatic microlens arrays since a microlens typically consists only of one lens element of material such as fused silica.\textsuperscript{3}

The distortions introduced by the lens system influence the quality of the spectral measurements captured at the detector. In this paper, we investigate the question of how to design a plenoptic lens system with filter array such that the quality of the measurements is optimized, taking into account the optical distortions. To answer this question we first derive a model for the response of the spectrally coded plenoptic optical system including diffraction and aberration effects via wave propagation techniques.\textsuperscript{4,5} Then we define a metric for estimating the quality of the spectral information measured at the detector. The metric evaluates spectral crosstalk introduced by the optical system, but also includes application specific information on targeted spectral distribution obtained from the detector measurements.

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Figure 1. Overview of plenoptic camera architecture including a spectral mask inserted into the main lens. The number of different spectral filters determine the number of spectral images created after processing of the sensor measurements.

The metric is then used to evaluate performances of different filter masks and to determine an optimal configuration. This optimization problem is split into two parts, a combinatorial optimization problem, evaluating different combinations of filter partitions, and a nonlinear constrained optimization problem, adjusting partition parameters to further improve the performance.

We demonstrate the proposed filter design method using the example of a Bayer pattern by (a) simulating the optical path of a spectrally-coded plenoptic camera, (b) analyzing the dependence of the simulated performance on diffraction and aberrations of the optical system and (c) demonstrating the effects of non-optimized and optimized filter designs on the system performance.

2. OPTICAL MODEL

To simulate the optical path of the plenoptic camera we perform a wave propagation analysis of light coming from a point source at infinity through main lens and microlens onto the sensor plane. We model the passing of an incoming wavefront $U$ through a lens with focal length $F_\lambda$ for the reference wavelength $\lambda$ which is described by

$$Q[-\frac{1}{f_\lambda}](x) = \exp\{\frac{\pi}{i}\lambda x^2\} U(x),$$

where $\kappa$ is the wave number. Free space propagation of a wavefront $U$ over a distance $z$ is given by $R[z](U(x_1)) = \frac{1}{\sqrt{4\pi z}} \int U(x_1) \exp\{\frac{\pi}{i}\lambda (x_2-x_1)^2\} dx_1$. For more details on these wave propagation operators we refer to.\(^4\) Now we combine the propagation through the main lens and the microlens optical system including an aperture transmission function $t_M$ for the main lens and an aperture transmission function $t_\mu$ to calculate the wavefront $U_{sensor}$ at the sensor plane as

$$U_{sensor}(M,t_\mu) = R[z_2]Q[-\frac{1}{F_\lambda}]t_\mu R[z_1]Q[-\frac{1}{F_\lambda}]t_M U,$$

for an incoming wavefront $U$, where $z_1$ is the distance between the main lens and the microlens, and $z_2$ is the distance between the microlens and the sensor.

In order to maximize angular resolution of the plenoptic architecture, we model the configuration in which a point source is located at infinity and the main lens system is focused on the microlens array plane (MLA plane). Using the thin lens formula for the main lens, the distance $z_1$ between the main lens and the MLA plane is set to $z_1 = F_\lambda$. Again using the thin lens equation, the distance between the microlens and the sensor plane $z_2$ is set to $z_2 = (1/f_\lambda - 1/z_1)^{-1}$. Since $z_1$ is very large compared to $z_2$ we can approximate $z_2$ with $f_\lambda$ as in.\(^6\)\(^,\)\(^7\) As a result, the wave propagation for a single reference wavelength $\lambda$ results in

$$U_{sensor}(M,t_\mu) = R[f_\lambda]Q[-\frac{1}{F_\lambda}]t_\mu R[F_\lambda]Q[-\frac{1}{F_\lambda}]t_M U,$$

with $U$ describing a planar wavefront.

Now we model an aperture mask to be inserted into the pupil plane of the main lens. We define an aperture mask to be a partition $\mathcal{P}$ of the aperture into a set of non-overlapping cells covering the circular aperture of
the main lens of diameter $D$. Each cell $c_i, i = 1, \ldots, M$, has a spectral response function $\rho_i(\lambda)$ where $\lambda$ is the wavelength parameter. First we model light passing through the filter array considering only a single spectral response $\rho^s$. For this case the aperture code reduces to a mask that transmits light only through those cells that have spectral response $\rho^s$. This mask is given by the following aperture transmission function

$$t_{\rho^s}(u, v, \lambda) = \begin{cases} \rho^s(\lambda), & \text{if } \exists i \in \{1, \ldots, M\} \text{ such that } (u, v) \in c_i \in \mathcal{P} \text{ with } \rho^* = \rho_i, \\ 0, & \text{otherwise} \end{cases}, \quad (3)$$

where $u, v$ are the spatial coordinates in the aperture plane.

Now we can define the wavefront arriving at the sensor plane as

$$U_{\text{sensor}}\{t_{\rho}, t_{\mu}\} = \mathcal{R}[f_{\lambda}]Q[-1/f_{\lambda}]\{|t_{\mu}\} \mathcal{R}[F_{\lambda}]Q[-1/F_{\lambda}]\{|t_{\rho}, U\}, \quad (4)$$

where $t_{\mu}$ is the aperture transmission function for partition $\mathcal{P}$ and response function $\rho_i$, and $t_{\mu}$ is the transmission function of a clear aperture of a microlens with diameter $d$. The propagation onto the microlens array plane is denoted as

$$U_{\text{MLA}}\{t_{\rho}\} = \mathcal{R}[F_{\lambda}]Q[-1/F_{\lambda}]\{|t_{\rho}, U\}. \quad (5)$$

In this paper, we restrict our analysis to on-axis lenslets only. To extend the analysis to off-axis lenslets we have to tilt the incoming wavefront $U$ and include a translation into the location of the aperture transmission function $t_{\mu}$.

### 2.1 Example of Bayer pattern

In this section we consider the example of the Bayer pattern, i.e., a combination of red, green, and blue spectral filters, where twice as much light passes through the green than through the red or blue filters. In order to ensure rotationally symmetric filtering in the aperture plane, we choose a ring layout for the 3-filter pattern, filling a circular aperture with three nested annular rings. The innermost ring is the blue filter, the green filter is in the middle, and the red is the outermost ring (see Fig. 2). In order to have twice as much light passing through the green ring than through the red and blue ring, we allocate the area covered by the rings to have a distribution of $1/4 : 1/2 : 1/4$ for blue, green, and red. This results in diameters of the three rings to be $\delta_1 = 0.5, \delta_2 = 0.866, \delta_3 = 1$ and center wavelengths $\lambda_1 = 450nm, \lambda_2 = 550nm, \lambda_3 = 650nm$. We assume the spectral response functions $\rho_i$ to be a bandpass filter with corresponding center wavelength $\lambda_i$. For each center wavelength $\lambda_i$, we can compute the focal lengths $f_i$ and $F_i$ of microlens and main lens using thin-lens approximation. The focal length of the main lens is calculated as

$$F_\lambda = \frac{1}{(n_M(\lambda) - 1)/(1/R_1 - 1/R_2)} \quad (6)$$

with refractive index $n_M(\lambda)$ and radii of curvature $R_1, R_2$. For a planar convex microlens the radius $R_2$ is infinite. Consequently the focal length of a planar convex microlens with refractive index $n_\mu(\lambda)$ and radius of curvature $R_\mu$ is approximated by (see also$^9$)

$$f_\lambda = \frac{R_\mu}{n_\mu(\lambda) - 1}. \quad (7)$$

In our example we assume Fused Silica for the microlens array and BK7 for the main lens. Refractive indices for these materials are given for a reference wavelength, and can be computed for other wavelengths using the Sellmeier dispersion formula.$^8$

For $\lambda_1 = 500nm$ and $\lambda_2 = 1.625nm$ equal to the focal lengths of the main lens and microlens at reference wavelength $\lambda = 588nm$, and lens diameter $D = 4mm$ of the main lens and $d = 130mm$ of the microlens, we show the responses $|U_{\text{MLA}}\{t_{\rho_i}\}|$ and $|U_{\text{sensor}}\{t_{\rho}, t_{\mu}\}|$ for individual aperture transmission functions $t_{\rho_1}, t_{\rho_2}, t_{\rho_3}$ of the main lens in Fig. 2. For better visualization of the diffraction effects we display $|U_{\text{MLA}}\{t_{\rho_i}\}|$ and not $|U_{\text{MLA}}\{t_{\rho_i}\}|^2$ as would be for displaying the point spread function (PSF) of the main lens system at the MLA.
Figure 2. Main lens system response $|U_{MLA}\{t_{\rho_i}\}|$ at the MLA plane for the three different spectral bands of the annual Bayer filter layout (left): blue (a), green (b), and red (c). The gray discs represent the lenslets. The response at the sensor $|U_{sensor}\{t_{\rho_i}\}|$ is shown for blue (d), green (e), and for red (f).

plane. Whereas the responses $|U_{MLA}|$ at the MLA plane looks like the familiar PSF of a conventional imaging system, the responses $|U_{sensor}|$ show images of the different cells of the pupil plane partition. Notice how diffraction rings are present in the space which is occupied by an image of a different spectral band (see (e) and (f)). This overlap can lead to spectral crosstalk in sensor measurements.

3. QUALITY METRIC FOR SENSOR DATA

3.1 Characterization of crosstalk at the MLA plane

The light passing through the main lens should ideally come to focus at the MLA plane, forming a very small spot. Due to diffraction effects and lens aberrations, such ideal case can not be achieved, and energy of a PSF focused on a certain lenslet may leak over to other microlenses, causing crosstalk at the MLA plane. Figure 2(c) shows an example of such crosstalk for the outer most ring in the partition. The throughput of PSF energy transmitted by the on-axis microlens incident on the sensor we compute as

$$Q_{MLA}(\rho_i) = \frac{\int \int U_{sensor}\{t_{\rho_i}\}(\eta, \xi, \lambda)d\eta d\xi d\lambda}{\int \int U_{MLA}\{t_{\rho_i}\}(x, y, \lambda)dxdy d\lambda}.$$  

3.2 Characterization of spectral crosstalk at the sensor

The image of the aperture mask on the sensor is not simply the same image scaled by the magnification factor of the microlens imaging system. Diffraction effects, Chromatic aberration, and lens aberrations are distorting the image causing images of non-overlapping cells in the aperture mask to overlap at the sensor plane. Such overlap causes spectral cross-talk at the sensor plane. Therefore, not an entire cell area, but a reduced one may contain the object’s spectral information intended to be filtered. In order to measure the performance of the system, we measure the spectral information on the sensor inside a superpixel $S$, the sensor area under a microlens, that is
not effected by cross-talk. To achieve that goal, we define the overlapping regions between two cell images on the
sensor as
\[ \Delta_i = \bigcup_{j \neq i} \left\{ \left( \eta, \xi \right) \in S \mid \int U_{\text{sensor}} \{ t_{p_i} \} (\eta, \xi, \lambda) d\lambda \neq 0 \right\} \cap \left\{ \left( \eta, \xi \right) \in S \mid \int U_{\text{sensor}} \{ t_{p_j} \} (\eta, \xi, \lambda) d\lambda \neq 0 \right\} \right\}. \quad (9) \]

Evaluating the areas of \( \Delta_i \) gives us a measure for how many pixels exposed to light passing through only a single filter response are in a superpixel. The light collected at location \( (\eta, \xi) \) on the sensor is described by
\[ J_{\text{sensor}}(\rho_m)(\eta, \xi) = \int U_{\text{sensor}} \{ t_{p_m} \} (\lambda, \eta, \xi) \tau(\lambda) d\lambda, \quad (10) \]
where \( \tau(\lambda) \) is the spectral sensitivity of the detector. The final spectral information for spectral response function \( \rho_m \) computed from the sensor measurements in the non-overlap area for the on-axis spatial location, similar to the method in,\(^1\) is defined as
\[ I(\rho_m) = \int_{S \setminus \Delta_m} J_{\text{sensor}}(\rho_m) d\mu, \quad (11) \]
with \( \mu \) being an integration measure that we choose to be the Lebesgue measure in this paper. Consequently, we compute the information contained in the areas of spectral overlap as
\[ I_{\Delta_m} = \frac{\int_{\Delta_m} J_{\text{sensor}}(\rho_m)}{\sum_n I(\rho_n)}. \quad (12) \]

### 3.3 Distribution of captured information over different spectral filters

For a given application it may be desired to capture spectral information according to a specific distribution over the filters. For example, the Bayer pattern contains twice as many green filters compared to red and blue since it is matching specific characteristics of the human visual system. For other applications, such as a detection or classification task, one might want to have a different distribution, e.g. higher response in blue than red due to required discriminating power between signals in the blue and red region of the light spectrum.

As a general model, we assume a target distribution given by discrete values of \( \alpha_m, m = 1, \ldots, M \) with \( 0 < \alpha_m \leq 1 \) and \( \sum \alpha_m = 1 \) for \( M \) spectral filters with responses \( \rho_1, \ldots, \rho_M \). In order to match the target distribution \( \{ \alpha_m \} \), the information collected at the sensor should satisfy
\[ \frac{I(\rho_m)}{\sum_n I(\rho_n)} \approx \alpha_m. \quad (13) \]

The difference between the distribution of captured spectral information and the target distribution is measured by a distance measure \( \text{dist}(\frac{I(\rho_m)}{\sum_n I(\rho_n)}, \alpha_m) \). In this paper we choose \( \text{dist}(\frac{I(\rho_m)}{\sum_n I(\rho_n)}, \alpha_m) \) to be
\[ \text{dist}(\frac{I(\rho_m)}{\sum_n I(\rho_n)}, \alpha_m) = \left| \frac{\alpha_m^{-1} \cdot I(\rho_m)}{\sum_n I(\rho_n)} - 1 \right|. \quad (14) \]

### 4. OPTIMIZATION OF FILTER LAYOUT

As a first step, we restrict the layout of the aperture code to being parameterized in an efficient way with a low-dimensional parameter set, consider the case of a circular aperture and assume the cells to be ring segments. A ring segment is given by its diameter \( \delta \), an inner radius \( r_0 \), an angular span \( \phi \), and an angular offset \( \phi_0 \) (see Fig. 3). Assuming a circular aperture of radius \( R \), we impose the following constraints on the radial partition \( P_R \):
The disk is divided into \( N \) nested rings \( R_n \) of diameters \( \delta_n \) with \( n = 1, \ldots, N \) and inner radii \( r_{0,n} = \delta_n - r_{0,n-1} \) with \( r_{0,0} = 0 \) and \( r_{0,N-1} + d_N = R \). Each ring \( R_n \) is divided into \( M(n) \) ring segments \( c_{n,m} \) parameterized by \( r_{0,n,m}, \delta_n, \phi_{n,m}, \text{ and } \phi_{0,n,m} \). Since the ring segments are required to form a partition of the aperture, the sum of the angular spans of the segments in a ring add up to \( 2\pi \). Each segment has a spectral response function \( \rho_{n,m}(\lambda) \)
Figure 3. Parameterization of a ring segment with diameter $\delta$, inner radius $r_0$, angular span $\phi$, and angular offset $\phi_0$ inside a disc of radius $R$.

associated with it. That means each cell $c_{n,m}$ of the aperture code is characterized by its spatial region described by $(\delta_n, r_{0,n}, \phi_{n,m}, \phi_{0,n,m})$ and its spectral response function $\rho_{n,m}(\lambda)$ for a specific $n$ and $m$ and wavelength $\lambda$.

This parameterization allows a circular aperture to be partitioned into rings, like those shown in Fig. 2, but also into pie chart segments (as in Fig. 3) and a mixture of both.

We want to answer the question of how to best choose the parameters of the cells forming the partition given a specific performance metric. That means in the case of a radial partition $P_R$, we want to determine the optimal diameters of the rings and the optimal angular spans of the ring segments according to minimizing an application specific cost function $C$. To answer this question we set up the following constrained optimization problem assuming a radial partition.

$$\begin{array}{ll}
\text{minimize} & C(x) \\
\text{subject to} & g(x) \leq 0 \\
& h(x) \leq 0 \\
\text{with optimization variable} & x \in \mathbb{R}^{N+2} \sum_{n=1}^{N} (M(n)) \\
\end{array}$$

with

$$x_i = \delta_i, \quad i = 1, \ldots, N,$$

$$x_i = \phi_{n,m}, \quad i = N + 1, \ldots, N + \sum_{n=1}^{N} (M(n)),$$

$$x_i = \phi_{0,n,m}, \quad i = N + \sum_{n=1}^{N} (M(n)) + 1, \ldots, N + 2 \sum_{n=1}^{N} (M(n)),$$

for $n = 1, \ldots, N, m = 1, \ldots, M(n)$,

$g$ being a linear constraint function, and $h$ being a nonlinear constraints function that may be used to compute, e.g., lower bounds on cell areas (see at the end of this section).

In the case of the annular partition, the linear constraints reduce to

$$\begin{align*}
\sum_{n=1}^{N} \delta_n &= R \\
0 &\leq \delta_n \leq R \\
M(n) &= 1 \\
\phi_{n,1} &= 2\pi \\
\phi_{0,n,1} &= 0 \\
r_{0,n} &= \delta_n - r_{0,n-1}, \quad \text{for } n = 1, \ldots, N.
\end{align*}$$
We design the cost function to take into account the cross-talk at the MLA-plane as well as spectral cross-talk at the sensor and distribution of captured information over different spectral filters. Since these measures are based on the wave propagation and integration over certain areas, they are highly non-linear and non-convex. Therefore, in general, we can not assume the optimization problem to be convex and have to use solvers that apply to non-convex constraint optimization problems.

We define the cost function to include the throughput at the MLA plane (Eq. 8), spectral overlap (Eq. 12) as well as deviation from the spectral target distribution (Eq. 14) as follows:

\[
C = w_1 \cdot \max_{m=1,...,M} \left|1 - Q_{MLA}(\rho_m)\right| + w_2 \cdot \max_{m=1,...,M} \frac{\int_{\Delta m} J_{sensor}(\rho_m) \, d\rho}{\sum_{n} I(\rho_n)} + w_3 \cdot \max_{m=1,...,M} \left|\frac{\alpha_m^{-1} \cdot I(\rho_m)}{\sum_{n} I(\rho_m)} - 1\right|
\]  

(15)

for weights 0 \leq w_i \leq 1 and \sum_i w_i = 1, where \{\alpha_m\}_{m=1,...,M} is the spectral target distribution.

The optimization problem in (15) includes a non-linear constraint function h that we have not considered so far. This function can calculate a lower bound on the size of a filter cell depending on the minimal resolvable spot size on the sensor and the magnification factor of the microlens. The circle of the size of the minimal resolvable spot size on the sensor, is derived using geometric optics principles.\(^1\)

5. SIMULATION RESULTS

We consider the task of designing a spectral mask for a lens system with specs described in the first table in Fig. 6 targeting a Bayer-filter-type spectral response distribution on the sensor, i.e. twice as many green pixels as red and blue. The microlens array is positioned one focal length away from the main lens. We choose two types of aperture mask partitions, the first consisting of three annuli-shaped cells \(c_n, n = 1, 2, 3\) of diameter \(\delta_n < R\), coded with red, green, and blue spectral responses with center wavelengths \(\lambda_1 = 450nm, \lambda_2 = 550nm,\) and \(\lambda_3 = 650nm\) ((a),(b) in Fig. 5). In this case, we have two optimization variables \(\delta_1, \delta_2\) and constraints \(0 < \delta_n < R, \delta_1 + \delta_2 < R, n = 1, 2\) and \(\delta_3 = R - \delta_1 - \delta_2\). The cells of the second partition form pie-chart segments, i.e. \(N = 1, M(n) = 4,\) and \(c_m, m = 1, 2, 3, 4\) with \(\delta_m = R - \delta_1 - \delta_2\) ((c) in Fig. 5), variables \(\phi_m, m = 1, \ldots, 4, \phi_{0,1}\) (neglecting index \(n\) since \(N = 1\)) and constraints \(\sum_m \phi_m = 2\pi, 0 \leq \phi_m, \phi_{0,1} \leq 2\pi\). Whereas the pie-chart partition produces narrow PSFs at the microlens plane for the different filters, annular partitions spread out the total energy at the microlens plane more resulting in extended depth of focus.\(^9\) Figure 4 shows responses \(|U_{MLA}|\) for the annular and the pie-chart partition. The asymmetry in \(|U_{MLA}|\) for the pie-chart partition is clearly visible. Whereas the total energy is spread out over the lenslet more for the annular partition, the very narrow inner spots of \(|U_{MLA}|\) for the outer rings of the filter mask lead to increased resolution at the MLA plane.

![Figure 4: Responses |U_{MLA}| of the annular and pie-chart partitions for a aberration-free main lens.](http://proceedings.spiedigitallibrary.org/)
weights for spectral overlap and deviation from the spectral target distribution we set to \( w_2 = w_3 = 0.5 \). The Matlab routine \textit{fmincon} is used to solve the nonlinear constrained optimization problem.

Fig. 5 shows the light intensity on the sensor for different configurations of the filter mask without optimization over the partition parameters. The annular layout with red at the outside suffers from severe spectral crosstalk caused by the optical distortions caused by the lenses and the filter partition, whereas having red inside and green outside reduces the effects of the optical distortions on the spectral crosstalk. Aberrations of main and microlens cause asymmetry of the imaged partitions. Results of the optimization of all configurations are listed in the table in Fig. 6. The pie-chart configuration (c) creates the least cross-talk at the sensor and yields minimum total cost \( C \). Its optimized version does not vary much compared to the starting configuration. For the two annuli configurations, the optimization leads to significant decrease of the cost and noticeable adjustment of the ring diameters with (b) outperforming (a). Annuli configurations may have, however, advantages compared to the disc segmentation in applications that require omnidirectional filtering of the rays through one spectral filter or that require good depth-of-focus performance.

![Fig. 5. Responses \( |U_{sensor}| \) for blue, green, and red for different filter layouts and aberrated main and micro lenses without optimization of the partition parameters.](image)

6. CONCLUSIONS

We introduced an optimization framework for designing the spatial layout of a spectrally coded mask inserted into the pupil plane of the main lens of a plenoptic camera. The optimization merit function evaluates spectral crosstalk at the sensor as well as similarity of the captured spectral distribution to an application-specific target distribution. Constraint optimization is performed over a parameterized aperture mask that can represent annular patterns as well as pie-chart segments and a mixture of both types. We demonstrated the benefit of an optimized Bayer pattern mask over a non-optimized one.

REFERENCES


Figure 6. Optical system specifications (top) and results for the optimization of the three filter layouts (bottom).