Composite versus multichannel binary phase-only filtering

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Multichannel filtering and its inherent capacity for the implementation of data-fusion algorithms for high-level image processing, as well as composite filtering and its capacity for distortion-invariant pattern-recognition tasks, are discussed and compared. Both approaches are assessed by use of binary phase-only filters to simplify implementation issues. We discuss similarities and differences of these two solutions and demonstrate that they can be merged efficiently, giving rise to a new category of filters that we call composite-multichannel filters. We illustrate this comparison and the new filter design for the case of rotation-invariant fingerprint recognition. In particular, we show that the gain in terms of encoding capacity in the case of the composite-multichannel approach can be used efficiently to introduce multichannel-filter reconfigurability. © 1997 Optical Society of America

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1. Introduction

Real-time optical pattern-recognition systems have been studied extensively over the past few years. Most of the current realizations use ferroelectric liquid-crystal (FLC) technology.[1] However, the gain in speed is partially balanced, in this case, by a limitation on the coding capacity of such spatial light modulators (SLM's), which are generally binary encoding. Another issue is related to the need for distortion invariance with which optical correlators are not naturally endowed. Therefore, distortion-invariant filters must be designed. Various techniques have already been proposed that integrate the coding limitations of the commercially available SLM.[2,3] However, none of these techniques optimally uses the available coding capacity of the SLM's.

The purpose of this paper is twofold. First, it is an attempt to bypass the limitation in design of composite phase-only filters (POF's) based on FLC technology that is due to the binary-encoding capacity of FLC SLM's. This is done by suggestion of a better use of the available encoding capacity by the spatial ar-

rangement of the spectral-plane information. This gain in capacity can be used, for instance, to introduce filter programmability, as is discussed in Section 3. The second point concerns a comparative analysis between multiple-channel and composite filtering in terms of discrimination capability for a given encoding-filter capacity by use of a FLC SLM. For the sake of simplicity, we limit our analysis to the VanderLugt architecture. Extensions to other configurations, such as joint transform correlators, are possible.[4]

To illustrate this analysis, we consider the case of distortion-invariant optical pattern recognition. Because distortion-invariant filters have to be encoded on existing and commercially available SLM's, device constraints have to be incorporated into the filter design. This is the main motivation behind the design of composite filters such as POF's.[3,5] When real-time processing is required the filter design is, in practice, limited to a binary POF (BPOF). We restrict our analysis to this case. In addition, to illustrate our investigation we consider the conventional fingerprint recognition and classification task.[6] We then address the issue of rotation invariance of a fingerprint. If we consider, for instance, that the composite filter is made up of N references, each of them being either a rotated version of a fingerprint or its corresponding spectrum, the overall rotation invariance will then be related to the number of references N that can be recorded on the SLM implementing the composite filter. This establishes a direct and simple criterion for evaluating the in-

variance capacity of the different composite filters in terms of encoding capacity.

Similarly, to make this comparison more relevant we use an optimization criterion in the correlation plane, namely the peak-to-correlation energy (PCE), where the correlation energy is estimated over the whole plane. This criterion is a conventional one for assessing the performance of filtering algorithms. As we use BPOF's, the signal-to-noise ratio is less relevant and the PCE is a good criterion for comparing the possible performances of the different techniques proposed in this paper, particularly in terms of peak sharpness and discrimination capabilities. The appropriateness of this criterion is discussed for each option in what follows.

2. Conventional Composite Binary Phase-Only Filter Approach

A composite BPOF can be designed in several ways (see, for instance, the survey paper by Kumar[5]). Here, to establish a relevant comparison between each option we consider the following strategy: The training set is made up of weighted spectra of rotated versions of a fingerprint. This situation is very close to a synthetic discrimination function strategy.[7]

To create a composite filter H from a set x_i of N references, we proceed as follows. We first compute the Fourier transform of the database images, denoted X_i. A composite filter is then built as a linear combination of the different spectra of the basis. The BPOF H is then obtained by use of the following binarization scheme[8]:

$$H = \text{sgn}\left[\Re\left(\sum_{i=0}^{i=N-1} \omega_i X_i\right)\right], \quad (1)$$

where $\Re(x)$ represents the real part of x and ω_i represents the weight of the spectrum X_i. To obtain a good performance, we need to optimize the weights. To obtain the optimal weights, we have to choose a criterion in the correlation plane that is based on the correlation peaks y_i for each image of the set. We suggest that the uniformity be used as the criterion. This uniformity can be optimized by the minimization of the following cost function:

$$C(H) = \frac{\sigma[\text{PCE}(y_i)]_{i=0\ldots N-1}}{\text{PCE}(y_i)_{i=0\ldots N-1}}, \quad (2)$$

where $\overline{x_i}$ represents the average of x_i and σ denotes the standard deviation. From unitary initial weights ω_{i0}, we obtain first the filter H_0 and then the responses PCE (y_{i0}). We suggest that the ideal weights ω_i can be calculated by use of the following expression:

$$\omega_i = [\text{PCE}(y_{i0})]^{-\alpha}, \quad (3)$$

where $0.5 \leq \alpha \leq 1.5$. For practical purposes, we choose a value of α that minimizes the cost function for each filter. The advantage is that the filter is calculated by use of a criterion that takes optimization of the whole correlation plane into account.

Fingerprint Image   Fingerprint Spectrum

5 references   10 references
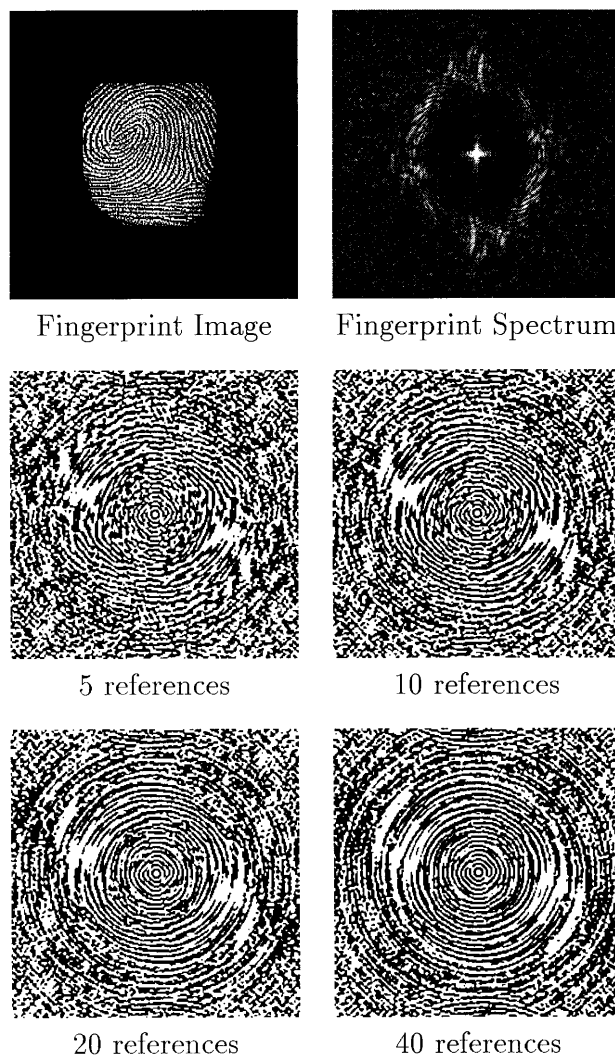
20 references   40 references

Fig. 1. Fingerprint image, fingerprint spectrum, and conventional composite filters: These binary filters are PCE invariant by rotations of 5°, 10°, 20°, and 40°, for the images with 5, 10, 20, and 40 references, respectively.

However, the principle of spectrum superimposition and the binarization process lead us to rapid saturation of some areas of the filter plane, which results, in fact, in a limit on the number of references that can be considered with such an approach. This has been observed in practice with a BPOF[9] and similarly with a joint transform correlator.[10] To have an idea of the number of references that can be encoded on a standard 256×256 pixels FLC SLM with this composite-filtering technique, we have designed four conventional composite filters for 5, 10, 20, and 40 references, respectively. The 5° invariance filter was designed with five fingerprints rotated from $-2°$ to $+2°$, with a 1° step (Fig. 1). The 10°, 20°, and 40° invariant filters were designed with 10, 20, and 40 references, respectively, spaced with a 1° angle.

To test these filters, we take a fingerprint and rotate it by $-30°$ to $30°$. Each rotated image is then correlated with the different conventional composite filters. The PCE responses are normalized with re-
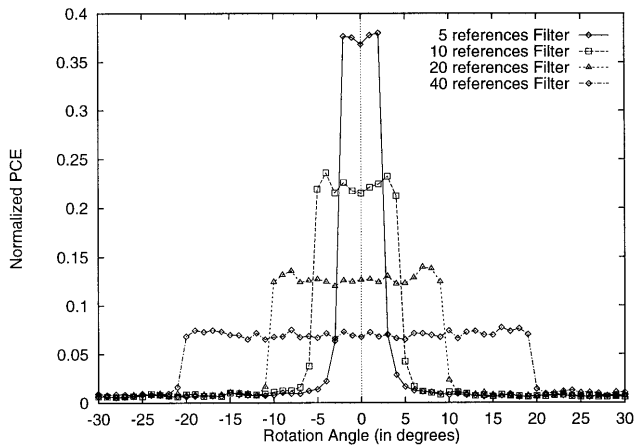
Fig. 2. Uniformity of the composite filters.

(a)

(b)

Fig. 4. Multichannel approaches: (a) The BPOF and binary fan-out optics are separate in each channel. (b) The BPOF and binary fan-out optics are merged in each channel.

spect to the PCE of a single reference filter. The results, presented in Fig. 2, show that the PCE evolves inversely proportionally to the square root of the number of references used to construct the rotation-invariant filter until saturation occurs. In fact, the appearance of the patterns on the filter as continuous and uniform means that saturation has occurred. No saturation effect has been observed here because of the large size of the SLM (this effect is more obvious when a 128×128 pixels SLM[10] is used). Therefore, the maximum number of references that can be encoded on a standard FLC SLM can be computed easily for a given application.

Thus, to test target rejection 100 different fingerprints were applied with our four composite filters. Figure 3 shows that discrimination is very good for each filter. The reference index represents the number of the reference in the input plane. The matched reference is the 55th. This result confirms what is generally encountered in the literature.[6]

3. Conventional Multichannel Binary Phase-Only Filter Approach

The multichannel approach is different in its principle. The main characteristic is that multiple corre-
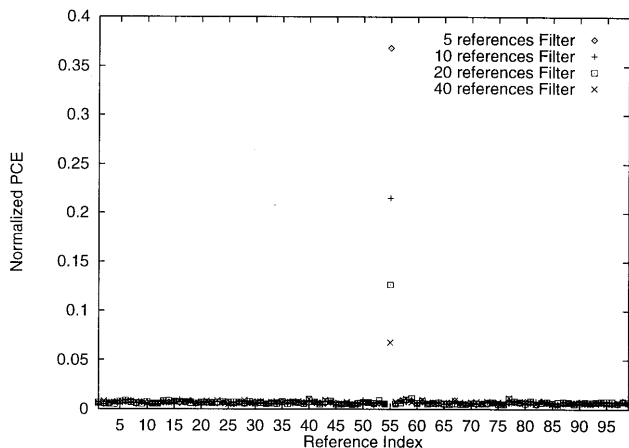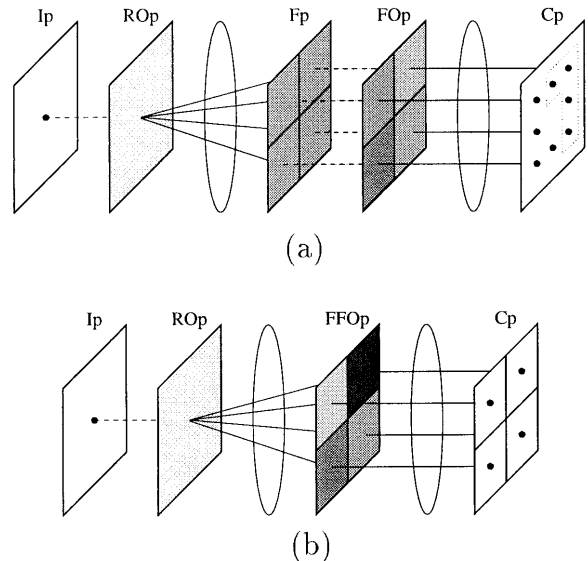

Fig. 3. Discrimination of the composite filters.

lations are performed in parallel (spatial or wavelength multiplexing) or sequentially (temporal multiplexing), and the result is interpreted afterwards. At this point several solutions can be proposed.[11] The multichannel filter can be operated by use of a time-multiplexing procedure.[7] Several correlations are performed sequentially, and the results are then compared. The consequence is a reduction in processing speed. Therefore, here we consider only the case of spatial multiplexing by use of a thin phase transparency (in practice, a SLM).

The advantage in this case is related to the fact that the correlation plane can be optimized with respect to multiple correlation peaks. This enables more complex rejection procedures to be used, as is explained below. We consider, in our first approach, that a multichannel approach is characterized basically by the implementation of several correlations in parallel with the same SLM. According to the VanderLugt architecture, the input plane is made up of a SLM displaying either gray-level or binary input pictures, with replication optics (ROp) generating multiple spectra of the input image in the Fourier plane (Fig. 4).

Similarly, the filter plane is made up of a SLM implementing the BPOF and fan-out optics, producing several correlation planes. In the first step we consider that the channels are independent. This means that the cross talk resulting from the input-picture truncation can be neglected. However, the use of a pure parallel configuration can appear to be of little interest if the processing performed in the correlation plane is not taken into account. Multichannel correlators are relevant for implementing complex image-processing tasks dealing, for instance, with hierarchical or data-fusion procedures.[12] Thus, such architectures become truly interesting

when the multichannel correlators are programmable. This capacity for programming assumes that the number of channels can be reconfigured quickly when, for instance, different filter sizes are presented (e.g., a multiresolution-type approach). Speed of reconfiguration results practically in the need for programmable fan-out optics for both the input and the filter planes. The most demanding case occurs when both the filter and the channel number are reconfigured at the same frame rate.

Many solutions can be proposed to implement these fan-out optics. For the sake of simplicity and (refreshing-) rate compatibility, it is preferable to implement the reconfiguration optics and the filter with the same technology, i.e., by use of FLC SLM's. The consequence is that only binary diffractive elements can be encoded (in practice, binary gratings with different orientations and possibly with different periods are encoded). This generally requires a particular spatial arrangement of the gratings to avoid multiple-order overlapping.

With consideration of these assumptions, the setups shown in Fig. 4 can be proposed. Regarding the filter design, each filter (Fp) in each channel can be optimized separately for a given additional binary fan-out optic (FOp) [Fig. 4(a)]. The alternative consists of including the fan-out optics in the filter design [Fig. 4(b)]. The consequence is an encoding-capacity reduction, but in contrast only one SLM is necessary and alignment issues are greatly simplified.

These two types of multichannel binary filters can be built as described below. To simplify the expression, we restrict our illustration to a simple case, i.e., a four-channel correlator. The generalization to n channels is straightforward. In both cases, the four different composite filters are designed as described in Section 2, but with two differences. The first concerns the size of the filter. If we consider that we have four channels, the area of each filter will be divided by 4. Therefore the filters H_l must be reduced to a size of 128×128 pixels, resulting in the following filter-plane expression:

$$H(i, j) = \text{sgn}\left\{ \Re\left[\sum_{l=1}^{l=4} H_l(i - d_{li}, j - d_{lj}) \right] \right\}, \quad (4)$$

where the pairs (d_{li}, d_{lj}) are (0, 0), (128, 0), (0, 128), and (128, 128) for all (i, j), as $0 \le i < 256$, $0 \le j < 256$, and where H_l is defined by

$$H_l(i, j) = \sum_{k=0}^{k=N-1} \omega_k X_{lk}(i, j). \quad (5)$$

In fact, each spectrum has a infinite extent in the Fourier plane. But the filters H_l will be constructed as a superimposition of truncated spectra (i.e., to the filter size). We assume that the spectral density outside the filter pupil can be neglected.
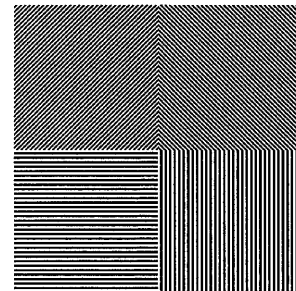
The second difference is in the system setup. In our first approach we consider that the BPOF and the fan-out optics are implemented in two separate planes; in our second approach we consider that the

(a) Channel Layout

| Channel 2 | Channel 4 |
| Channel 1 | Channel 3 |
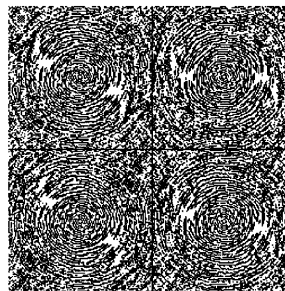
(b) BPOF   (c) Fan-Out Optics

(d) Peak Layout

Channel 4 Order +1	Channel 1 Order -1	Channel 2 Order -1
Channel 3 Order +1		Channel 3 Order -1
Channel 2 Order +1	Channel 1 Order +1	Channel 4 Order -1

(e) Correlation Plane

Fig. 5. First pure multichannel setup: (a) the channel layout, (b) the BPOF, (c) the binary fan-out optics, (d) the peak layout in the correlation plane, and (e) the correlation plane for channel 3 recognition. Since the fan-out optics are binary, there are two correlation peaks for each channel (the peak and its conjugate).

fan-out optics are included directly in the filter design.

A. Multichannel Approach with Separate Fan-Out Optics

In Fig. 5, we represent the filter plane (Fp), the replication-optics plane (ROp), the fan-out-optics plane (FOp), and the correlation plane (Cp). This approach is called the pure multichannel approach in what follows. Since each filter shown in Fig. 5(a) is a 10° rotation-invariant composite filter, the entire filter plane results in an equivalent ±20° rotation-invariant composite filter.

As a result of the use of FLC SLM's for implementing the fan-out optics, each optics configuration associated with each filter is necessarily a binary grating. To avoid multiorder overlapping, it is necessary that the spectra be positioned and oriented correctly.   An

illustration of this point is given by Fig. 5(c). The complete filter plane is then defined as follows:

$$H'(i,j) = H(i,j)D(i,j) \tag{6}$$

where $D(i,j)$ is a basic grating configuration, and its arrangement is defined by [even(x) is equal to 0 if x is odd and to 1 if x is even] the following:

$$
\begin{aligned}
D(i,j) = &\left[2\left(\text{even}\left\{\frac{i}{2}\right\} - \frac{1}{2}\right)\right]_{0 \le i < 128, 0 \le j < 128} \\
&+ \left[2\left(\text{even}\left\{\frac{j-i}{2}\right\} - \frac{1}{2}\right)\right]_{0 \le i < 128, 0 \le j < 128} \\
&+ \left[2\left(\text{even}\left\{\frac{i}{2}\right\} - \frac{1}{2}\right)\right]_{128 \le i < 256, 0 \le j < 128} \\
&+ \left[2\left(\text{even}\left\{\frac{i+j}{2}\right\} - \frac{1}{2}\right)\right]_{128 \le i < 256, 128 \le j < 256}.
\end{aligned}
$$

B. Multichannel Approach with Merged Fan-Out Optics

Here we consider that the fan-out optics are included in the filter itself. So a spatial carrier, typically a prism function, is applied before the binarization of the composite filter, which is designed by the superimposition of the reference spectra. The expression for H_l becomes

$$H_l(i,j) = C_l(i,j) \sum_{k=0}^{k=N-1} \omega_k X_{lk}(i,j), \tag{7}$$

where $C_l(i,j)$ is a spatial carrier defined by

$$C_l(i,j) = \exp[i2\pi(d_i i + d_j j)]. \tag{8}$$

The pair (d_i, d_j) represents the peak shift in the correlation plane. In each channel, the shifts are $(-64, -64)$, $(-64, 64)$, $(64, -64)$, and $(64, 64)$, respectively. Figure 6 illustrates this arrangment: The multichannel filter and its fan-out optics correspond to a $\pm 20°$ rotation invariance. The multiorder effect is reduced considerably here because there is no binarization of the fan-out optics. The binarization operates on a combination of the filter and its optics.

C. Comparison of the Multichannel Alternatives

To compare both multichannel options we considered the normalized PCE's of both multichannel setups for $\pm 10°$ (Figs. 7 and 8) and for $\pm 20°$ (Figs. 9 and 10) rotation invariance. A common reference was introduced for comparison with the composite-filter results. The PCE's were estimated for several areas defined by the different correlation-plane channels. These channels are shown in Figs. 5(c) and 6(b).

We notice immediately that, for both $\pm 10°$ and $\pm 20°$ rotation invariance, the PCE in terms the pure multichannel approach provides better performance than does the multichannel approach with merged fan-out optics. This can be explained by the encoding-capacity reduction caused by the merging of the fan-out optics in the filter design in the second approach. However, the correlation-peak uniformity is lower in the pure multichannel setup. This

Channel 2	Channel 4
Channel 1	Channel 3

(a) Channel Layout
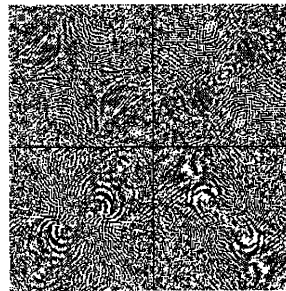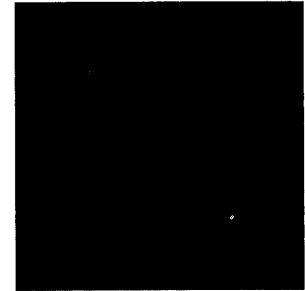
(b) Carriered BPOF   (c) Correlation Plane

Fig. 6. Second pure multichannel setup: (a) the channel layout, (b) the BPOF with a spatial carrier, and (c) the correlation plane. The peak layout in the correlation plane is located in the center of each channel.

is because of the efficiencies of our fan-out optics, which are different for each channel as a result of different orientations and periods, i.e., to the SLM pixelization.

In contrast, we observe (Fig. 5 and 6) that interpretation of the correlation plane is made easier with the off-axis BPOF than with the pure multichannel off-axis BPOF. Similarly, detection is better due to the combined optimization of the filter and its optics. The other consequence is an effect on the peak non-uniformity, which is considerably smoother.
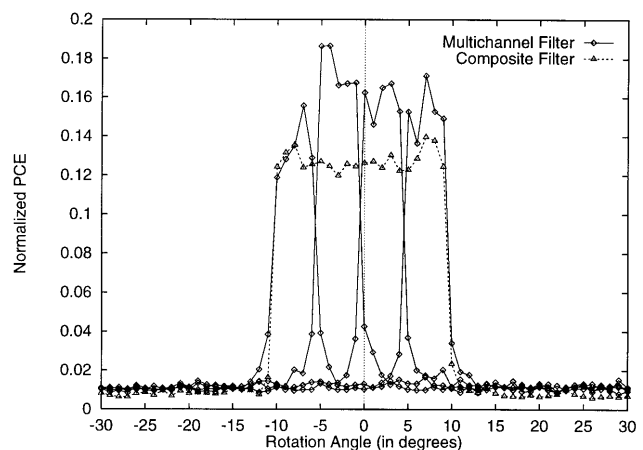

Fig. 7. PCE's for $\pm 10°$ invariant filters: The filters used are pure multichannel. The solid curves represent the PCE's of a multichannel filter in which the filter and fan-out are split.
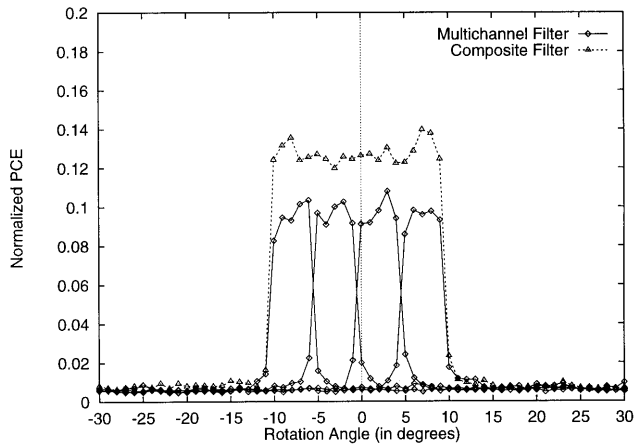
Fig. 8. PCE's for ±10° invariant filters: The solid curves represent the PCE's of a multichannel correlator in which the filter and fan-out are merged.

Another observable effect, inherent to both approaches, is channel discontinuity for rotated images that fall between two composite filters. This border effect results in the observation of two peaks in their corresponding channels, which means that, in each channel, the PCE is decreased. This behavior is to be expected when sectors of circle filters are used. This issue disappears, of course, when using different filters in each channel.

4. Composite-Multichannel Binary Phase-Only Filter Approach

The above analysis leads us naturally to combine the respective advantages of the two previous approaches. The filter is designed to make both better use of the SLM's encoding capacity and a smart interpretation of the detection plane, which is a characteristic of multichannel approaches. The idea consists of magnifying the input-picture spectrum with respect to each channel to enable spectrum overlapping. The first consequence is that the fan-out
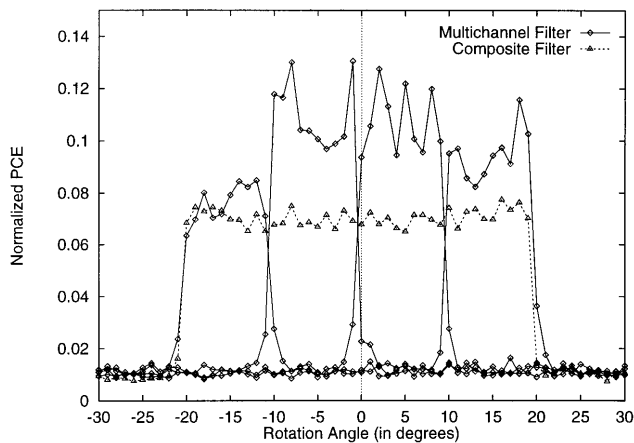
optics can no longer be separated from the filter design during the optimization procedure. As described in Section 3, two solutions can be considered:

• First, we consider two FLC SLM's, the first for the filter and the second for the fan-out optics. Both planes are optimized with respect to a cost function in the correlation plane, which takes channel separation into account. This generally is a complex optimization procedure and makes the setup sensitive to alignment problems.

• Second, we consider only one plane that merges both the overlapped filter and the optics. This option reduces the encoding capacity but makes optimization easier. According to this principle, the filter plane is calculated as shown in Fig. 11. We choose an overlap factor of close to 50%. The filter design starts with the application of a spatial carrier on each of the four composite filters. This operation is similar to what was described in Section 3.

The filter expression in this second case is

$$H(i,j) = \text{sgn}\left\{\Re\left[\sum_{l=1}^{l=4} \omega_l (C_l H_l)(i - d_{li}, j - d_{lj})\right]\right\}, \quad (9)$$

Fig. 9. PCE's for ±20° invariant filters: The solid curves represent the PCE's of a multichannel filter in which the filter and fan-out are split.

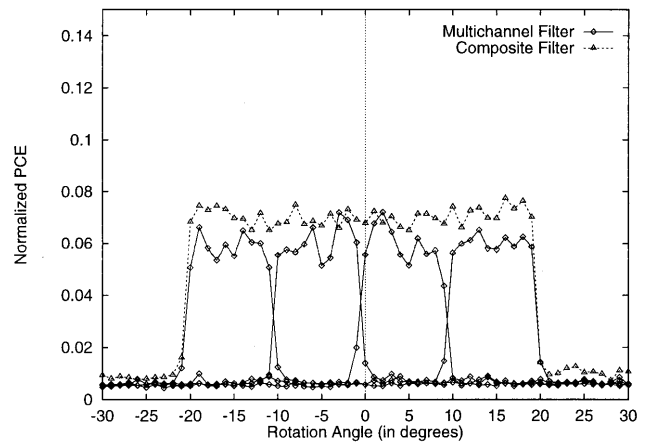Fig. 10. PCE's for ±20° invariant filters: The solid curves represent the PCE's of a multichannel setup in which the filter and fan-out are merged.
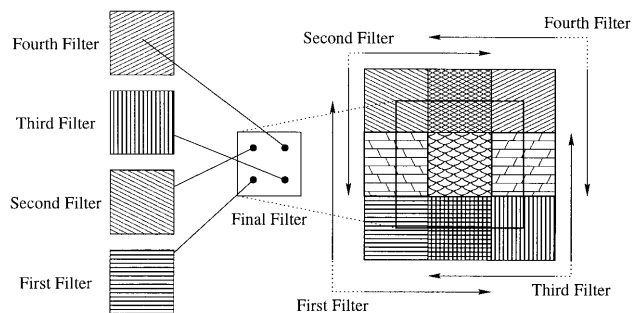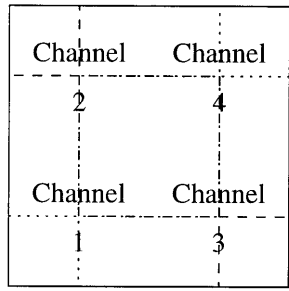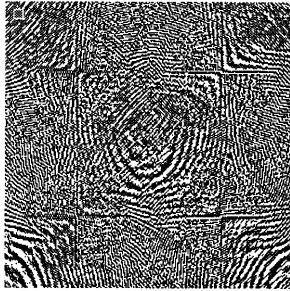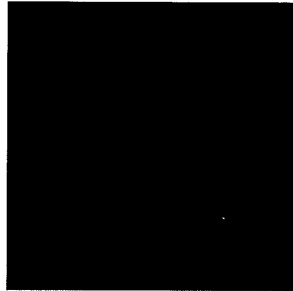

Fig. 11. Composite-multichannel filter design: First, a spatial carrier is applied to every composite filter. Second, the four composite filters are overlapped in the filter plane. Third, the filter is binarized.

(a) Channel Layout

(b) Carriered BPOF   (c) Correlation Plane

Fig. 12. Composite multichannel setup: (a) the channel layout, (b) the BPOF, and (c) the correlation plane. The correlation peak appears in channel 3.

Fig. 13. Composite-multichannel setup versus the pure composite and pure multichannel setups for $\pm 10°$ rotation invariance.

where $C_l(i, j)$ is a spatial carrier that defines the peak shift (d_{li}, d_{lj}) in the correlation plane. They are respectively for each channel, shifts to $(-64, -64)$, $(64, -64)$, $(-64, 64)$, and $(64, 64)$ pixels.

Next we consider a linear combination of these filters H_l, weighted by ω_l and shifted on each channel by the same amount (d_{li}, d_{lj}). Binarization is applied, yielding the filter of Fig. 12(b). The weights ω_l are optimized by use of the same procedure that was used in the conventional composite-filter design. As we can see this approach can be interpreted as a multichannel approach because physically separate planes are created while simultaneously having the characteristic of a composite-filter approach, because optimization is achieved over the whole filter plane for each correlation plane.

Therefore, the fan-out optics can be seen as a particular interconnection scheme rather than as pure multichannel fan-out optics. This is particularly true in the common central part where the four optics are merged, making the optics design very close to that of conventional array illuminators.[13] This approach is more powerful in terms of fan-out optics design, first because more degrees of freedom are available in the computation of the interconnects, and second because the optimization procedure involves the whole correlation plane, permitting crosstalk reduction and optimization of the filter response to the other channels.

Figures 13 and 14 display the normalized PCE for fingerprints rotated between $-30°$ and $30°$, applied to $\pm 10°$ and $\pm 20°$ rotation-invariant filters. We observe several results. First, the composite-

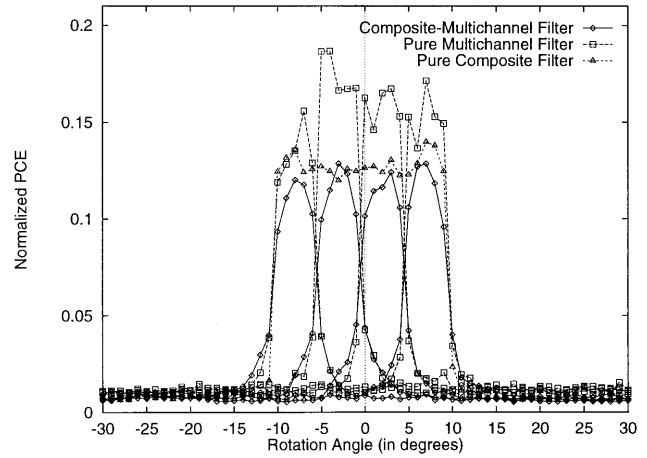multichannel approach is comparable with or better than the pure composite approach. It is better when the number of references increases, thereby confirming the influence of the saturation effect in the pure composite approach.

Second, the composite-multichannel approach is worse than or comparable with the pure multichannel approach. It is comparable when the number of references increases, thereby exhibiting better optimization of the encoding capacity as a result of overlapping spectra. Additional advantages of the composite-multichannel approach lie in the fact that only one SLM is used and the correlation plane is easier to interpretate. This is due to the fact that optimization of the peak response in each quarter takes account of the response in the other quarters.

5. Discussion

We have shown that the two concepts of multichannel and composite filtering can be combined efficiently: The first is characterized by a more complex multiple-target decision scheme, and the second by a more
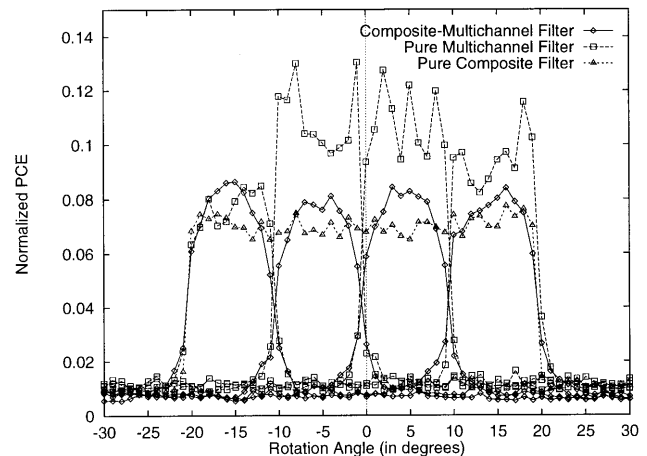

Fig. 14. Composite-multichannel setup versus the pure composite and pure multichannel setups for $\pm 20°$ rotation invariance.

complex optimization procedure in the filter design. Therefore, the composite-multichannel approach appears to be a good compromise between these two options and has been demonstrated to be better, in terms of global performance, than the two extreme cases.

Because of the overlapping principle and the optimization procedures that are applied, this solution can be considered as a composite approach, although it has the advantages of a multichannel approach because of the possible smart interpretation of the correlation plane resulting from the multiple-correlation-peak distribution. A last advantage lies in the fact that the fan-out optics can be included in the filter design without significant performance reductions. This makes programmability possible, which is a necessary feature in the multichannel approach.

In terms of encoding capacity, the composite-multichannel approach has been demonstrated to be the best compromise in particular when the number of references increases. Its performance is very close to that of a pure multichannel correlator but without the need for two SLM's. This is partly due to the fact that the entire encoding capacity is used during the optimization procedure. This point becomes more relevant when the references are different and when the optimization in the correlation plane is performed according to a nonindependant interpretation of each quarter (i.e., to the primitives or references presented or combined).

Practically, we have shown that the gain in encoding capacity results in a better distribution of the information encoded in the filter plane. This makes possible system reconfigurability and allows a real advantage of the multichannel approach to be obtained.

This approach has emphasized that the space–bandwidth product of an optical system based on Fourier optics can be used indifferently either to encode filter operation or to interconnect.[14] From this respect, conventional Fourier filtering can be seen as a fully interconnected operator, whereas the multichannel approach is a partially interconnected one. Thus it follows that the concept of composite-multichannel filter establishes a continuum between these two extreme cases. When the fan-out optics is encoded in the filter itself, the only difference lies in the interpretation made in the output plane with respect to what is presented at both the input and filter planes. From an optical viewpoint, there is no fundamental difference.

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