Wavelength-multiplexing system for single-mode image transmission

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The expanding use of optical communication by means of optical fibers and the situation of drastically increasing amounts of data to be transmitted urge the exploration of novel systems permitting the transmission of large amounts of spatial information by fiber with smaller spatial resolution. An optical encoding and decoding system is suggested for transmitting one- or two-dimensional images by means of a single-mode fiber. The superresolving system is based on wavelength multiplexing of the input spatial information, which is achieved with diffractive optical elements. Preliminary experimental results demonstrate the capabilities of the suggested method for the one- and two-dimensional cases. © 1997 Optical Society of America

Key words: Wavelength multiplexing, superresolution, optical communication.

1. Introduction

The resolution of a system is defined as the finest detail that can pass through the system without being distorted. Nowadays, when the amount of information to be transmitted increases while the required transmission time must rapidly decrease, a clear motivation for exploring superresolving optical systems arises. The motivation behind the superresolution field in general is to handle nonresolved details by use of given *a priori* information about the input signal. This *a priori* information may be characterized by such different groups as the object shape,[1,2] a single dimensional signal,[3] a polarization-restricted signal,[4] a temporally restricted signal,[5,6] and a wavelength-restricted signal.[7] If, for instance, it is known in advance that the signal's information is monochromatic, one may convert part of the spatial information into wavelength information in such a way that the aperture of the system is expanded synthetically on the basis of distinguishing between the signal information and system's capabilities.[8] This type of improving the spatial resolution of the system has been generalized by use of the space–bandwidth-product adaptation tool suggested in Refs. 9 and 10.

In this paper focusing is done over the wavelength-multiplexing superresolution characterization. The fundamentals of this approach were constructed in Ref. 7 by Kartashev and in Ref. 11 by Wiener. Later, Armitage *et al.*[12] proposed an optical implementation for one-dimensional (1-D) wavelength multiplexing for encoding objects and for correlation. In their setup the white-light point source (WLPS) was separated one dimensionally to its colors by use of a dispersive prism and was used for encoding the illuminated input object. Then the light was collected and input again into the fiber. The decoding setup was similar. In a similar encoding idea an extension to two dimensions and a white-light correlator between two two-dimensional (2-D) spatial distributions were suggested. However, the 2-D feature was achieved by use of an additional moving slit (time multiplexing).

Optical laboratory demonstrations of the above proposals were done by Bartelt, who used the different wavelengths of the white-light source for the transmission of signals,[13] image correlation,[14] coordinate transformation,[15] and height contouring.[16] The disadvantage to Bartelt's approach is that his setups contained expensive prisms (for wavelength multiplexing on the first axis) and moving elements (for time multiplexing on the second axis). Moreover, the image-transmission rate is limited as a result of the time multiplexing. Later, Paek *et al.*[17] suggested a real-time wavelength-multiplexing ap-

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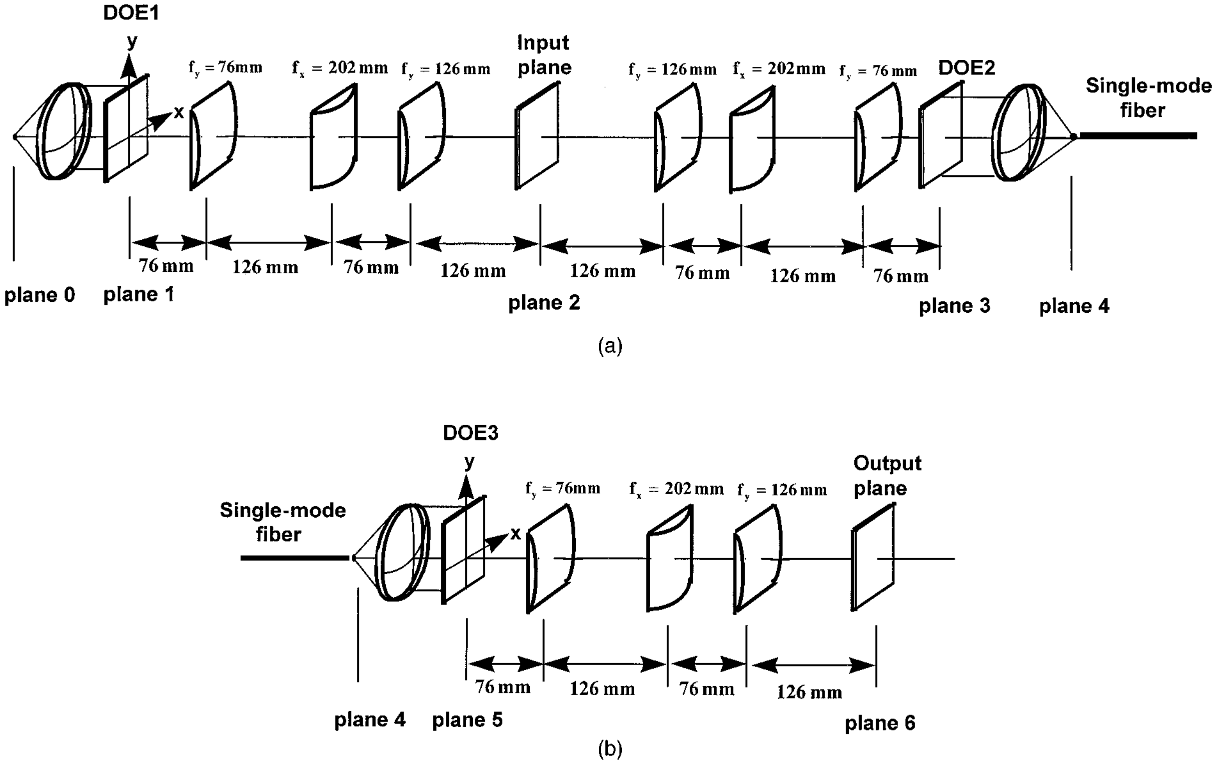


Fig. 1. Illustration of the suggested optical setup: (a) The encoding part. (b) The decoding part.

proach for transmitting 2-D information through a single-mode fiber. However, in their approach encoding of the input pattern was done with an exotic element coined the 2-D MC SELDA.

Friesem *et al.*[18] have suggested as well various optical setups for the parallel transmission of images through a single optical fiber. They suggested three main approaches for the transmission of 2-D images: angular–time multiplexing, wavelength–time multiplexing, and angular–wavelength multiplexing. The disadvantage of the first two methods is that they contain moving elements, and the third approach suffers from low light efficiency caused by the use of a slit. In addition, the transmission fiber mentioned in Ref. 18 is a multimode fiber and not a single-mode fiber, as in our suggestion.

In the approach suggested here the white-light source illuminates a diffractive optical element (DOE) to obtain the color spread. Every 2-D spatial location is encoded with a specific predetermined wavelength. Then the wavelength-multiplexing approach is implemented for encoding 2-D images, transmitting them by means of a single-mode fiber and then decoding them with a system that is similar to the encoding system. The final system is static (without moving components) and flexible to take into account the exact spectrum of the light source.

Let us introduce a terminological note about the notation used herein (taken from the discussion part of Ref. 12): "If a given lens with additional devices has a larger passband for spatial frequencies than this lens would have when used alone, then we talk about superresolution . . . " (p. 273). In this paper a fiber with a single-mode spatial bandwidth but a sufficient wavelength bandwidth is used. Thus, to avoid further controversies with respect to names, we coin our system a wavelength-multiplexing system.

2. Suggested System

The suggested setup for 2-D image transmission is illustrated in Fig. 1. The system consists of two parts. The first part includes encoding the spatial information contained in the input pattern into wavelength information (planes 0–3). The encoded distribution is then collected by a lens into a single spatial mode for transmission (plane 4). The encoding process is illustrated in Fig. 1(a). The second part of the system performs decoding of the information received in the other side of the fiber (planes 5 and 6) and is illustrated in Fig. 1(b).

At first, a WLPS is collimated into a plane wave by use of a lens. The collimated light reaches the first DOE, which consists of grating strips (as seen in Fig. 2). The number of strips is determined according to the spatial information along the vertical axis of the input pattern. For instance, if the filter consists of only one strip, a 1-D superresolution effect will be obtained. Each strip of the DOE creates a 1-D rainbow spread over the input plane (see Fig. 1). A partial range of wavelengths, arising out of the created rainbow, illuminates the corresponding strip of the input object. The spatial frequency of the gratings in each strip is determined in such a way that a different range of wavelengths illuminates different

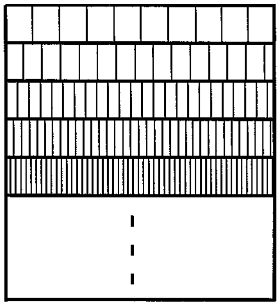


Fig. 2. DOE grating structure.

strips of the input object. That way, every 2-D spatial coordinate of the input object is encoded by a different wavelength.

The period of the grating in each strip must fulfill two conditions: First, even the highest-period rate must be low enough to ensure full spatial separation among the spectra of the different diffraction orders. Second, as mentioned above, the wavelength distribution coming from each strip must be shifted enough that, inside the aperture of the input pattern, each pixel is illuminated with a different wavelength. If, for instance, the experimental demonstration is designed for N × 2 pixel inputs (N as any integer number), the DOE may contain only two strips. The illustration of the color distribution over the input pattern for this case is shown in Fig. 3.

If the above-mentioned requirements are formulated mathematically for a two-strip-type DOE, the conditions to be fulfilled are as follows:

$$\frac{\lambda_0}{\Lambda_1} = \frac{\lambda_0 - \Delta\lambda/2}{\Lambda_2}, \tag{1}$$

$$2\,\frac{\lambda_0 - \Delta\lambda/2}{\Lambda_1} \geq \frac{\lambda_0 + \Delta\lambda/2}{\Lambda_2}; \tag{2}$$

where Λ_i denotes the period of the ith grating strip in the DOE, $i = 1$ designates the highest-period rate, λ_0 is the central wavelength of the WLPS, and $\Delta\lambda$ is the spectral bandwidth of the source. For a lens' focal length f the horizontal dimension of the input pattern L_x should be

$$\left(\frac{\lambda_0}{\Lambda_2} - \frac{\lambda_0}{\Lambda_1}\right) f = L_x. \tag{3}$$

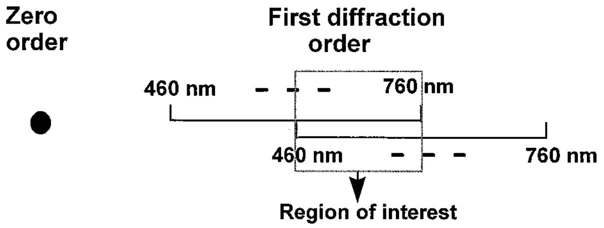


Fig. 3. Illustration of the color distribution over the input pattern.

Equation (1) ensures the proper displacement between the wavelength distributions caused by each strip so that different pixels of the input object are illuminated by different wavelengths. Expression (2) ensures that sufficient separation exists between the first and the second diffraction orders. Those considerations are illustrated graphically in Fig. 3.

In plane 2 the spectrum is spread to all its wavelengths that illuminate the input pattern placed in the first diffraction order created by the first DOE. According to our DOE design, each spatial pixel of the input is illuminated by a different wavelength. Thus a spatial-wavelength transformation is achieved. Note that the Fourier transform is performed along only the wavelength-spread direction (horizontal direction), while in the vertical direction imaging is performed [see Figs. 1(a) and 1(b)]. In plane 3 an additional Fourier transform is performed. There all the spatial information of the input plane is encoded by wavelength distribution. Thus in plane 3 the obtained field distribution is a summation of plane waves, while each plane wave is of a different wavelength and its amplitude is proportional to the spatial transmission of the specific pixel of the input pattern that is encoded with that specific wavelength.

The Fourier transform performed to propagate to plane 3 is once again anamorphic: a Fourier transform in the horizontal direction and imaging in the vertical one. Note that the plane wave obtained for each color in plane 3 is tilted since it starts from a different location in plane 2. To correct the plane wave's direction of propagation, we use an additional DOE. This DOE is identical to the first one. The direction correction is critical to the efficient collection of the light and to guiding the field distribution into the fiber. This second DOE is placed in the first diffraction order of the first DOE. In plane 4 the plane wave is focused to a point to be transmitted by means of a single-mode fiber.

The second part of the system is the decoding setup. It consists of a lens that enlarges the fiber point-source data back to their original dimensions. Then the plane wave is multiplied by a DOE, which is the same grating as the two before. An anamorphic Fourier transform (Fourier on the horizontal axis and imaging on the vertical axis) is performed while the beam is propagated from plane 5 to plane 6. In plane 6 full restoration of the input pattern is obtained. No spatial information is lost despite the fact that the image is transmitted throughout in a single-mode optical fiber.

3. Mathematical Analysis of the System

In this section a 1-D analysis of the suggested system is performed. An extension to two dimensions is straightforward. The spectral distribution of the WLPS is denoted by $S(\lambda)$. Since the white-light source is a point source, a collimated plane wave is obtained in plane 1. Thus the field distribution after the first DOE yields

$$u_1(x_1, \lambda) = S(\lambda)\exp\left(\frac{2\pi i}{\lambda}\frac{\lambda}{\Lambda}x_1\right), \tag{4}$$

where Λ is the period of the DOE grating. After performing the additional Fourier transform to propagate the light to plane 2, the obtained field distribution is

$$u_2(x_2, \lambda) = S(\lambda)\delta\left(x_2 - \frac{f\lambda}{\Lambda}\right), \tag{5}$$

where f is the focal length of the lens. When multiplied by the input pattern $G(x_2)$, the result obtained is

$$u_2(x_2, \lambda) = G(x_2)S(\lambda)\delta\left(x_2 - \frac{f\lambda}{\Lambda}\right). \tag{6}$$

By the passing of the plane wave to plane 3, an additional spatial Fourier transform is performed:

$$\begin{aligned} u_3(x_3, \lambda) &= \int_{-\infty}^{\infty} u_2(x_2, \lambda)\exp\left(\frac{-2\pi i x_2 x_3}{\lambda f}\right)\mathrm{d}x_2 \\ &= \exp\left(\frac{-2\pi i x_3}{\Lambda}\right)G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda). \end{aligned} \tag{7}$$

When the distribution from Eq. (7) is multiplied by the second DOE, which is the correction grating, the result obtained is

$$u_3(x_3, \lambda) = u_3(x_3, \lambda)\exp\left(\frac{2\pi i x_3}{\Lambda}\right) = G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda). \tag{8}$$

Thus, according to the result obtained with Eq. (8), u_3 is a plane wave with no spatial information. All the spatial information of $G(x)$ has been encoded as wavelength information. Thus $G(x)$ may be reduced to a point source to permit transmission throughout with a single-mode fiber. This light collection is realized in plane 4:

$$u_4(x_4, \lambda) = \delta(x_4)G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda). \tag{9}$$

Now u_4 is ready to be transmitted by means of a single-mode device such as a fiber. After the collimating lens the resulting field distribution of plane 5 becomes

$$u_5(x_5, \lambda) = G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda). \tag{10}$$

Then it is multiplied by the correction grating:

$$u_5(x_5, \lambda) = \exp\left(\frac{2\pi i x_5}{\Lambda}\right)G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda). \tag{11}$$

Performing the Fourier transform to propagate the beam to plane number 6 results in

$$\begin{aligned} u_6(x_6, \lambda) &= \int_{-\infty}^{\infty} u_5(x_5, \lambda)\exp\left(\frac{-2\pi i x_5 x_6}{\lambda f}\right)\mathrm{d}x_5 \\ &= G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda)\delta\left(x_6 - \frac{f\lambda}{\Lambda}\right). \end{aligned} \tag{12}$$

A careful examination of Eq. (12) reveals that all the wavelength information in $G(f\lambda/\Lambda)S(\lambda)$ is now back decoded into spatial information by the function $\delta[x_6 - (f\lambda/\Lambda)]$. Note that, for a uniform spectrum of the WLPS, which is also at least as wide as the bandwidth of $G(f\lambda/\Lambda)$,

$$G\left(\frac{f\lambda}{\Lambda}\right)S(\lambda) = G\left(\frac{f\lambda}{\Lambda}\right); \tag{13}$$

thus here all the spatial information of the input object G is decoded into spatial information. Note that the restriction of

$$\Delta\lambda_S \geq \Delta\lambda_G, \tag{14}$$

where $\Delta\lambda_S$ is the spectral bandwidth of S and $\Delta\lambda_G$ is the spectral bandwidth of $G(f\lambda/\Lambda)$, is needed to maintain all the information existing in the input pattern G.

4. Experimental Results

The optical setup illustrated in Fig. 1 was constructed in the laboratory. The chosen lenses' focal lengths are indicated in the figure. At first the system was demonstrated for a 1-D case. Instead of a DOE with several strips, a DOE with a single-strip grating was created. Three such DOE elements with a single strip were produced by a Scitex plotter and then reduced to sizes of 10 mm × 10 mm by use of a high-resolution reduction lens. The grating was designed to work with WLPS with a significant spectral range of 520–720 nm ($\lambda_0 = 620$ nm, $\Delta\lambda = 200$ nm). The WLPS was a halogen lamp. Most of the spectrum of such a lamp is concentrated in the red and infrared parts of the spectrum.

The period of the chosen grating was $\Lambda_1 = 10$ µm. The focal length of the lens was $f = 76$ mm. The input was also a grating with a period of 1 mm. Figure 4 demonstrates the experimental results obtained at the output of the system. As seen in Fig. 4(a), the grating was fully reconstructed. Note that the different spatial coordinates of the input grating image were obtained at different wavelengths. In Fig. 4(b) one can see the information reconstructed by only the green range of the spectrum, in Fig. 4(c) the information carried by the yellow range is shown, in Fig. 4(d) is shown the orange range of information, and in Fig. 4(e) is shown the red range. The camera that captured the experimental results was a CCD camera in which the infrared filter was removed.

The system needed for 2-D objects is exactly the

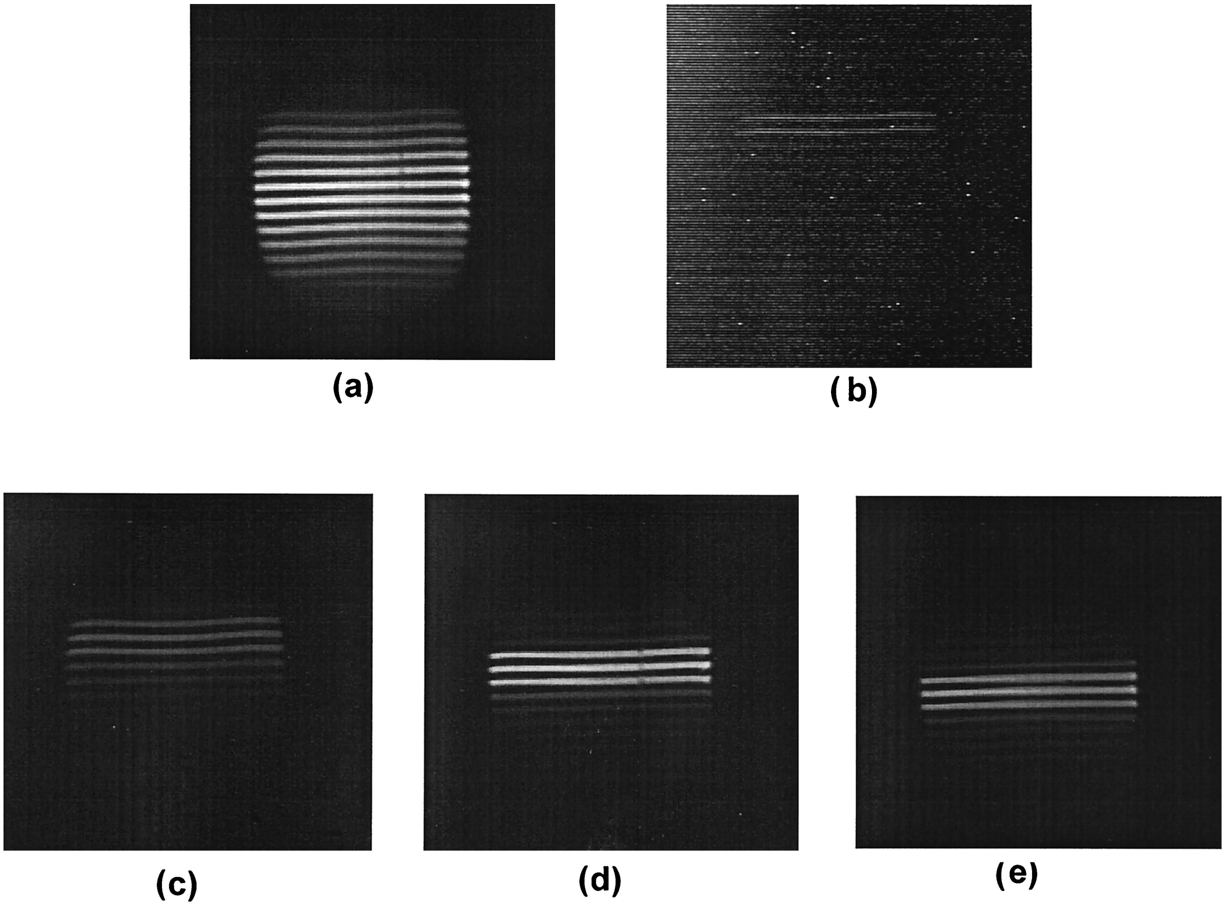


Fig. 4. (a) Obtained reconstruction in the output plane. (b) The information carried in the green spectral range. (c) The information carried in the yellow spectral range. (d) The information carried in the orange spectral range. (e) The information carried in the red spectral range.

same. The only difference is in the structure of the DOE's that, for two dimensions, contain two grating strips. Since the system has a large number of elements, the DOE must be efficient. Moreover, all three DOE's must be identical. The DOE in this case contained two strips with periods of $\Lambda_1 = 10$ μm and $\Lambda_2 = 14$ μm so that the two rainbows created by each strip caused the color distribution seen from Fig. 5. The input object contained two strips of gratings with periods of 1 and 2 mm [see Fig. 6(a)]. The output obtained after multiplexing the information transmitted through a single-mode fiber and demultiplexing is shown in Fig. 6(h). One can see the reconstruction of the input object.

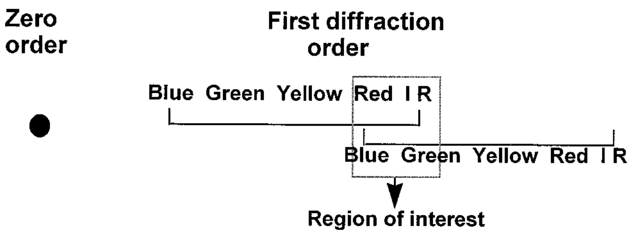
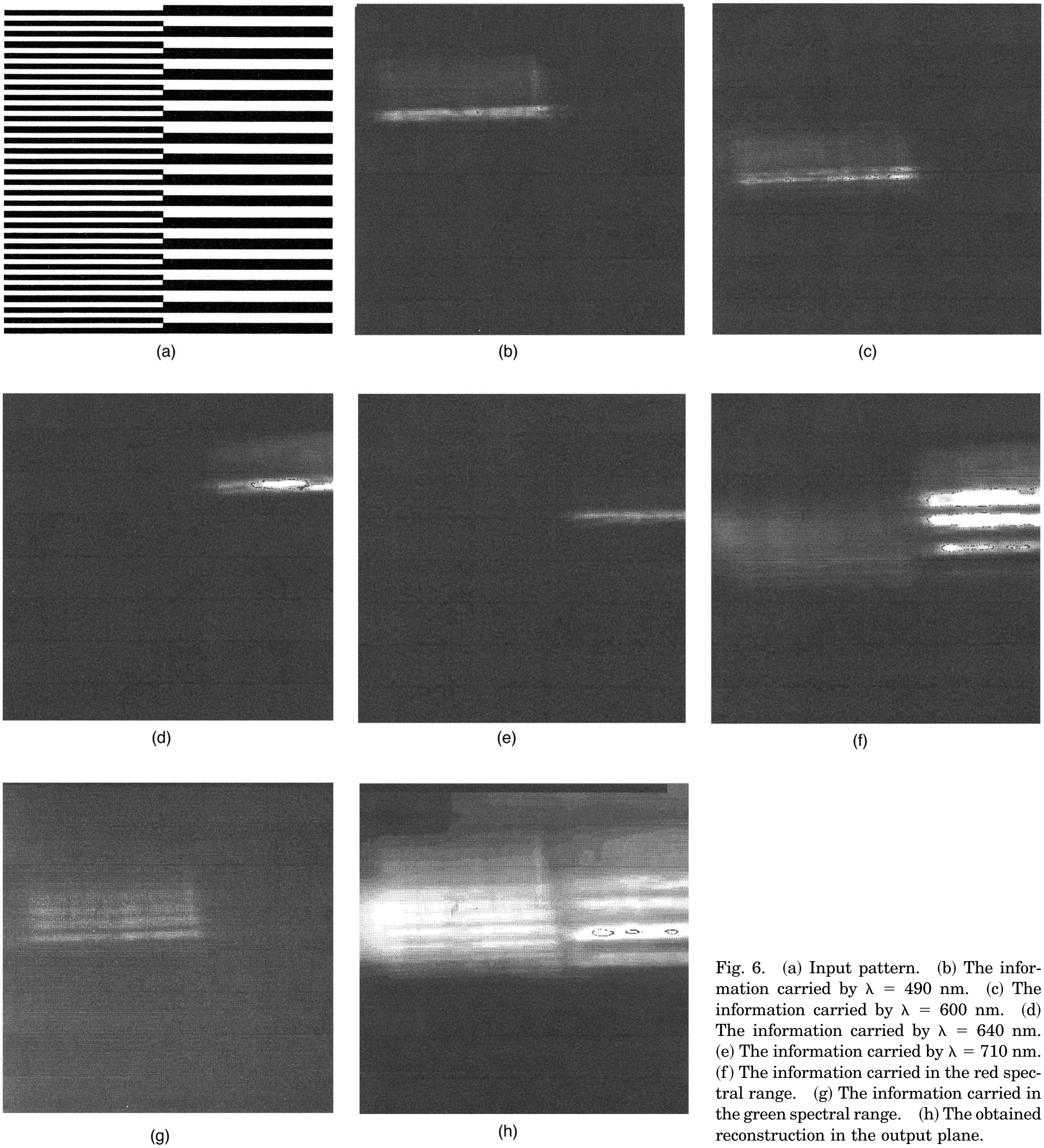


Fig. 5. Color distribution over the input pattern obtained in the 2-D experiment.

As explained in Sections 2 and 3, each spatial position of the output is obtained at a different wavelength. Figures 6(b)–6(e) illustrate this effect. These figures were obtained by the placement of narrow spectral filters of 490, 600, 640, and 710 nm, respectively, in the output plane. Figures 6(f) and 6(g) were obtained by the placement of broad red and broad green spectral filters, respectively, in the output plane.

5. Conclusions

In this paper a new approach for 1-D and 2-D wavelength-multiplexing encoding has been discussed theoretically and demonstrated experimentally for the 1-D and 2-D cases. The spatial resolution of the input object was codified by wavelength, while different wavelengths were assigned to different pixels of the input pattern. The wavelength distribution was then reduced to a single-source light and transmitted by means of a single-mode fiber. Then use of a similar decoding setup backconverted the wavelength information into spatial information. Note that the illumination source did not contain any wavelength information. In the output plane, the differing spatial information of the input pattern was represented by different wavelengths.



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 6. (a) Input pattern. (b) The information carried by λ = 490 nm. (c) The information carried by λ = 600 nm. (d) The information carried by λ = 640 nm. (e) The information carried by λ = 710 nm. (f) The information carried in the red spectral range. (g) The information carried in the green spectral range. (h) The obtained reconstruction in the output plane.

The suggested setup consists of DOE's and does not contain any moving elements. The capabilities of the approach were tested experimentally for the 1-D and 2-D cases.

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References

1. G. Toraldo Di Francia, "Resolving power and information," J. Opt. Soc. Am. A **45,** 497–501 (1955).
2. G. Toraldo Di Francia, "Degrees of freedom of an image," J. Opt. Soc. Am. A **59,** 799–804 (1969).

3. H. Bartelt and A. W. Lohmann, "Optical processing of 1-D signals," Opt. Commun. **42,** 87–91 (1982).
4. W. Gartner and A. W. Lohmann, "An experiment going beyond Abbe's limit of diffraction," Z. Physik **174,** 18 (1963).
5. M. Francon, "Amelioration de resolution d'optique," Nuovo Cimento Suppl. **9,** 283–290 (1952).
6. W. Lukosz, "Optical systems with resolving powers exceeding the classical limit," J. Opt. Soc. Am. A **56,** 1463–1472 (1966).
7. A. I. Kartashev, "Optical systems with enhanced resolving power," Opt. Spectrosc. **9,** 204–206 (1960).
8. A. W. Lohmann, R. G. Dorsch, D. Mendlovic, Z. Zalevsky, and C. Ferreira, "Space–bandwidth product of optical signal and systems," J. Opt. Soc. Am. A **13,** 470–473 (1996).
9. D. Mendlovic and A. W. Lohmann, "Space–bandwidth product adaptation and its application for superresolution: fundamentals," J. Opt. Soc. Am. A **15,** 558–562 (1997).
10. D. Mendlovic, A. W. Lohmann, and Z. Zalevsky, "Space–bandwidth product adaptation and its application for superresolution: examples," J. Opt. Soc. Am. A **15,** 563–567 (1997).
11. A. M. Weiner, J. P. Heritage, and E. M. Kirschner, "High-resolution femtosecond pulse shaping," J. Opt. Soc. Am. B **5,** 1563–1569 (1988).
12. J. D. Armitage, A. W. Lohmann, and D. P. Paris, "Superresolution image forming systems for objects with restricted lambda dependence," Jpn. J. Appl. Phys. **4,** 273–275 (1965).
13. H. O. Bartelt, "Transmission of two dimensional images by wavelength multiplexing," Opt. Commun. **28,** 45–50 (1979).
14. H. O. Bartelt, "Image correlation in white light by wavelength multiplexing," Opt. Commun. **29,** 37–40 (1979).
15. H. O. Bartelt, "One dimensional image transformation in white light," Opt. Commun. **38,** 239–242 (1981).
16. H. O. Bartelt, "Height contouring by wavelength multiplexing," Opt. Commun. **49,** 17–20 (1984).
17. E. G. Paek, C. E. Zah, K. W. Cheung, and L. Curtis, "All-optical image transmission through a single mode fiber," Opt. Lett. **17,** 613–615 (1992).
18. A. A. Friesem, U. Levy, and Y. Silberberg, "Parallel transmission of images through single optical fibers," Proc. IEEE **71,** 208–221 (1983).