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Two-dimensional optical filter and associated methods

Pritish Mukherjee

Sarath Witanachchi

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(45) **Date of Patent: Feb. 24, 2004**

(54) **TWO-DIMENSIONAL OPTICAL FILTER AND ASSOCIATED METHODS**

(75) Inventors: **Pritish Mukherjee**, Tampa, FL (US); **Sarath Witanachchi**, Tampa, FL (US)

(73) Assignee: **University of South Florida**, Tampa, FL (US)

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(22) Filed: **Oct. 4, 2001**

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Related U.S. Application Data

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(51) **Int. Cl.**[7] **G02B 6/06**
(52) **U.S. Cl.** **385/116**
(58) **Field of Search** 385/31, 32, 50, 385/115, 116

(56) **References Cited**

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Mukherjee, et al., "Novel Continuously Tunable High Spectral Rsolution Optical Filter for Two–Dimensional Imaging," Review of Scientific Instruments, vol. 72, No. 6, Jun. 2001.

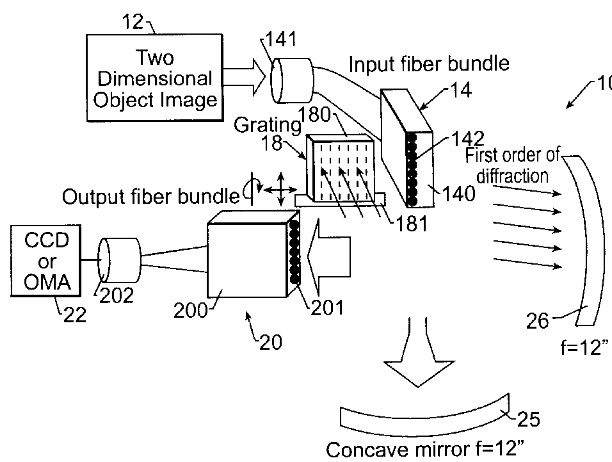
* cited by examiner

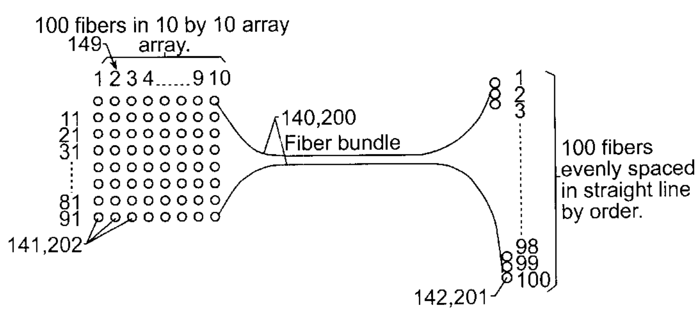
Primary Examiner—Euncha Cherry
(74) *Attorney, Agent, or Firm*—Smith & Hopen, P.A.; Molly L. Sauter

(57) **ABSTRACT**

An optical filter includes an input optical fiber bundle and an output fiber bundle. Each of the bundles has one end having the fiber ends substantially two-dimensionally arrayed and another end substantially linearly arrayed. Each input fiber is configured to receive a portion of a two-dimensional input image at the two-dimensional end and transmit the image portion to the one-dimensional end. A spectrally dispersive element receives the image portions from the input fiber bundle and outputs a predetermined spectral component to the output optical fiber bundle at the one-dimensional end, transmitting the image portion to the two-dimensional end. The output fiber bundle two-dimensional ends are arrayed in corresponding fashion to the first ends of the input fibers for spatially reconstructing the input image.

51 Claims, 12 Drawing Sheets





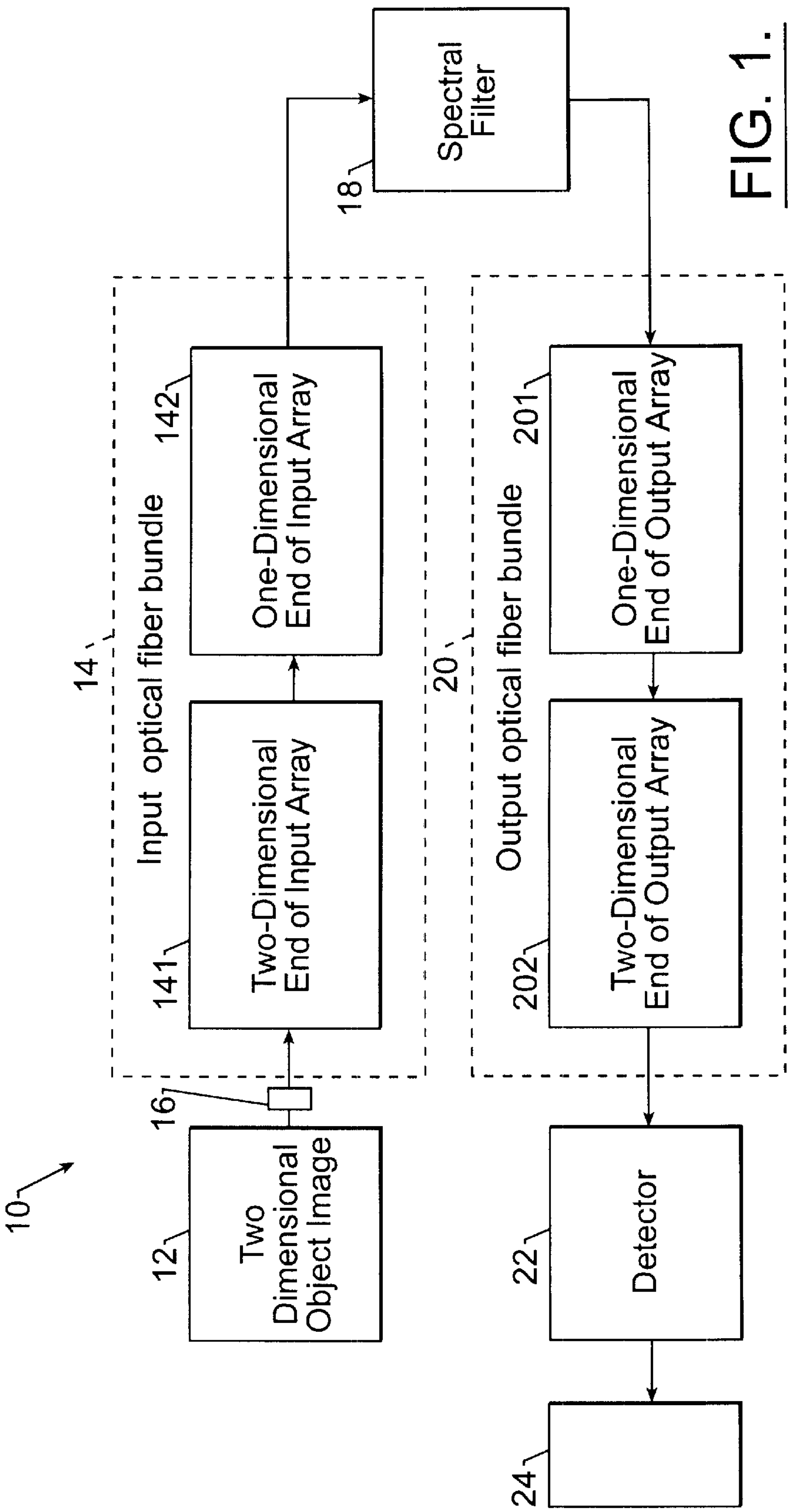
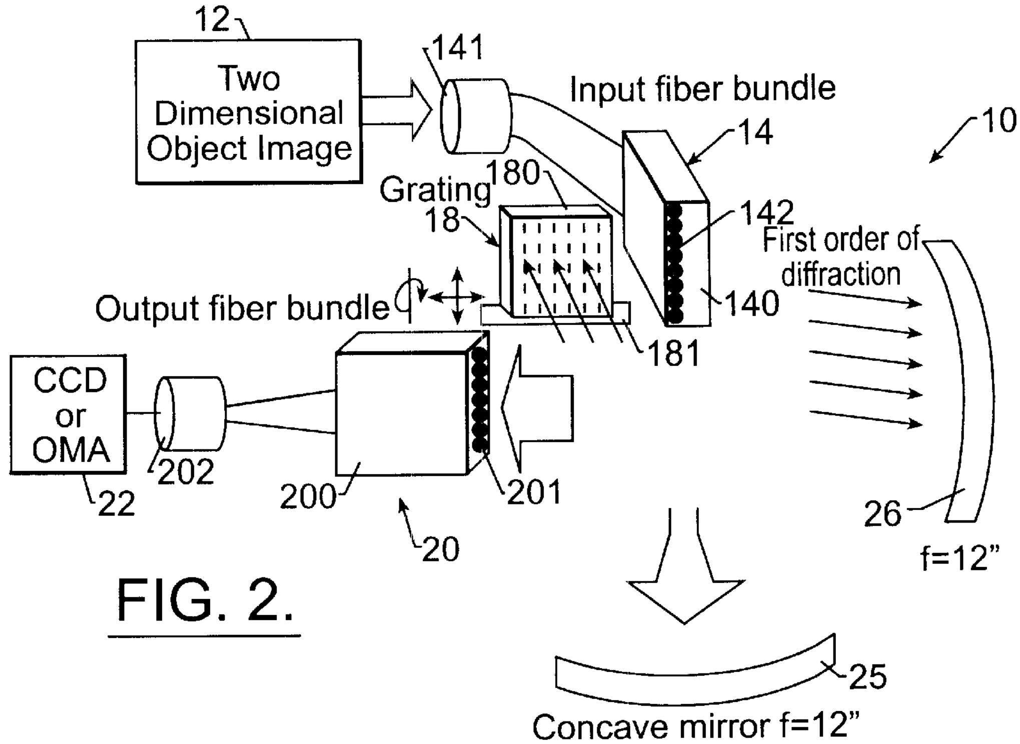
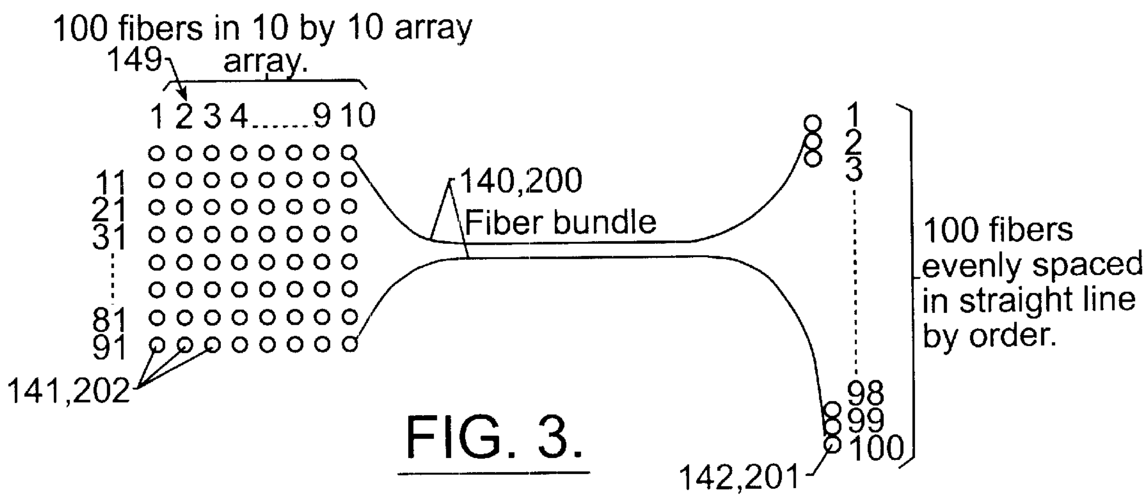

10
12
Two Dimensional Object Image
16
14
Input optical fiber bundle
141
Two-Dimensional End of Input Array
142
One-Dimensional End of Input Array
18
Spectral Filter
20
Output optical fiber bundle
201
One-Dimensional End of Output Array
202
Two-Dimensional End of Output Array
22
Detector
24

FIG. 1.



12
Two Dimensional Object Image
141
Input fiber bundle
14
10
Grating
180
18
142
First order of diffraction
Output fiber bundle
140
181
CCD or OMA
202
22
200
201
20
26
f=12"
25
Concave mirror f=12"

FIG. 2.



100 fibers in 10 by 10 array
149
array.
1 2 3 4......9 10
11
21
31
81
91
141,202
140,200
Fiber bundle
1
2
3
98
99
100
142,201
100 fibers evenly spaced in straight line by order.

FIG. 3.

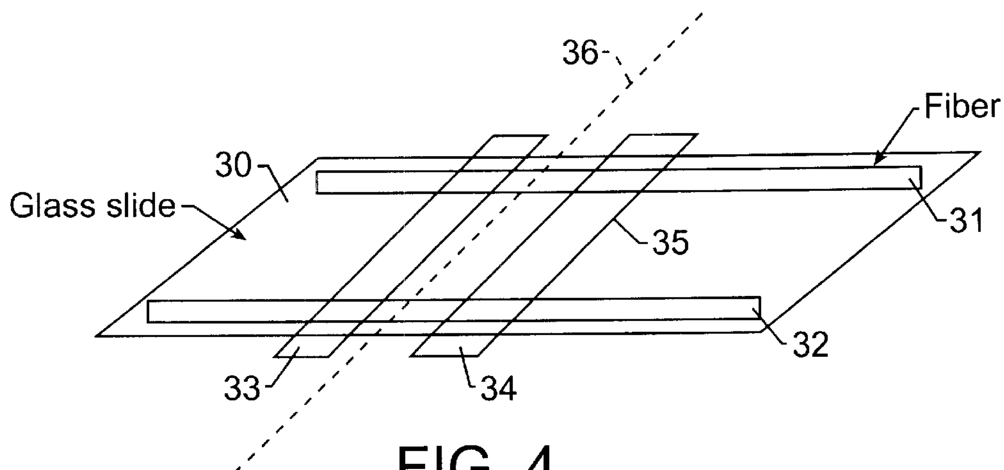


FIG. 4.

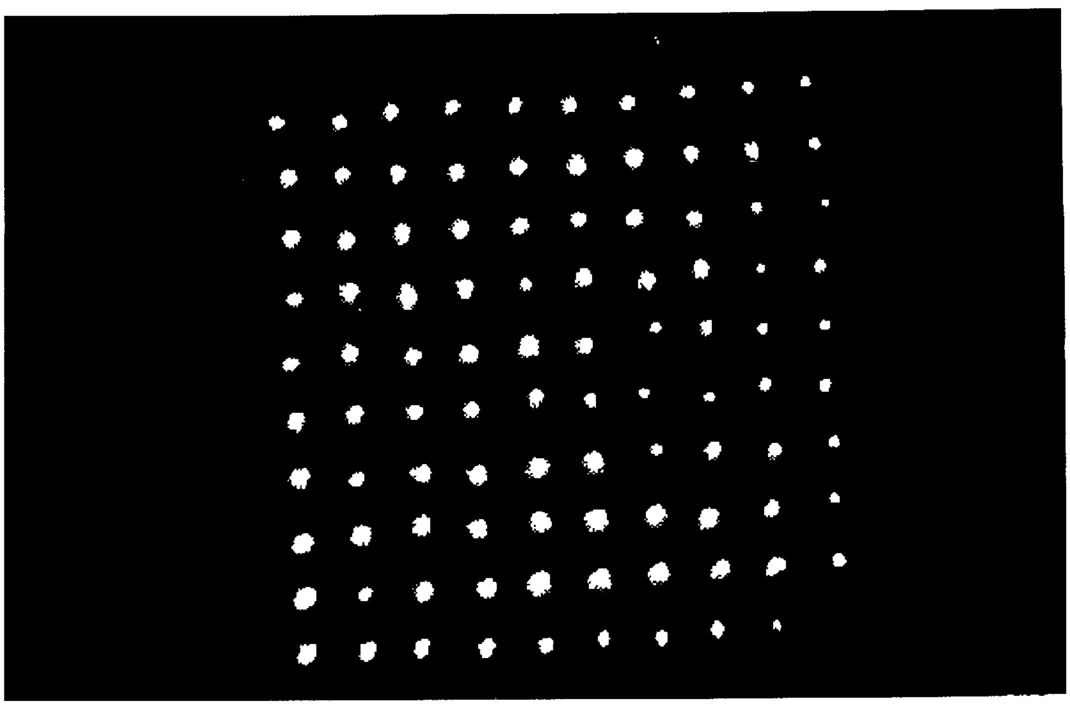


FIG. 5.

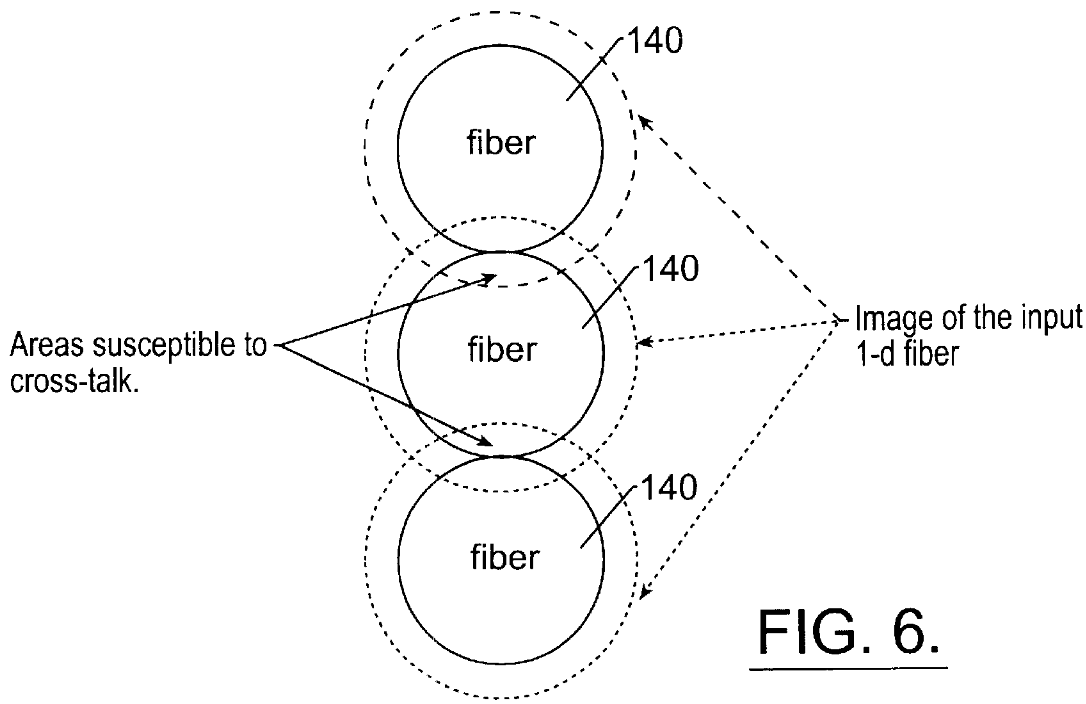

140
fiber
140
fiber
140
fiber
Areas susceptible to cross-talk.
Image of the input 1-d fiber

FIG. 6.

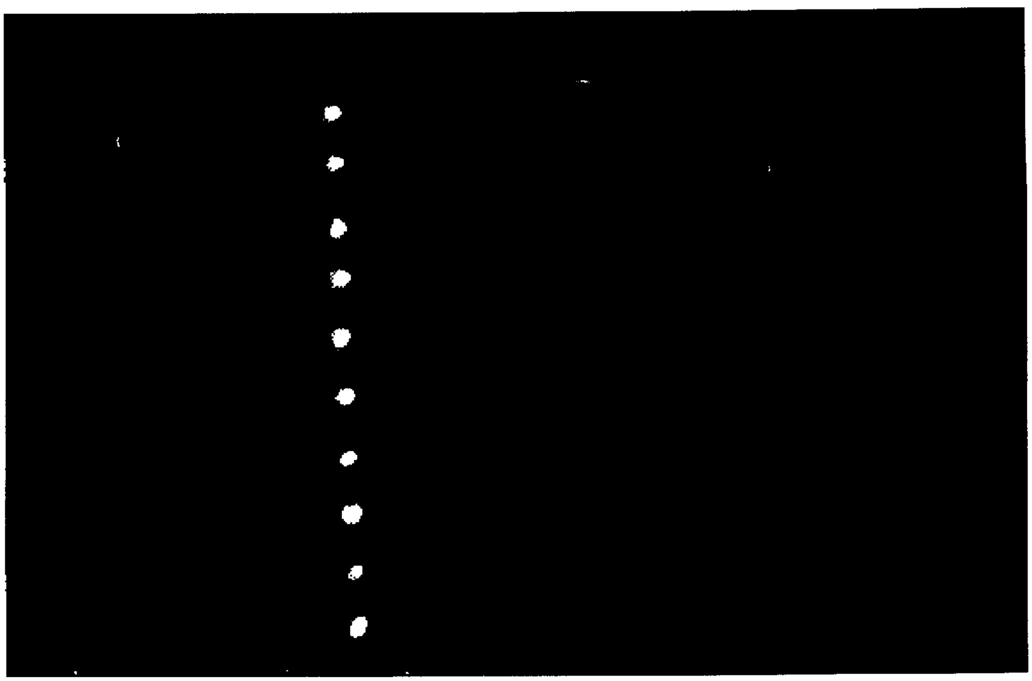


FIG. 7.

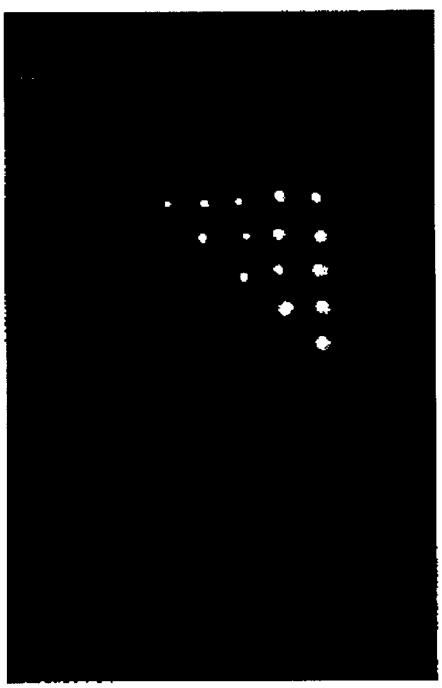


FIG. 8A.

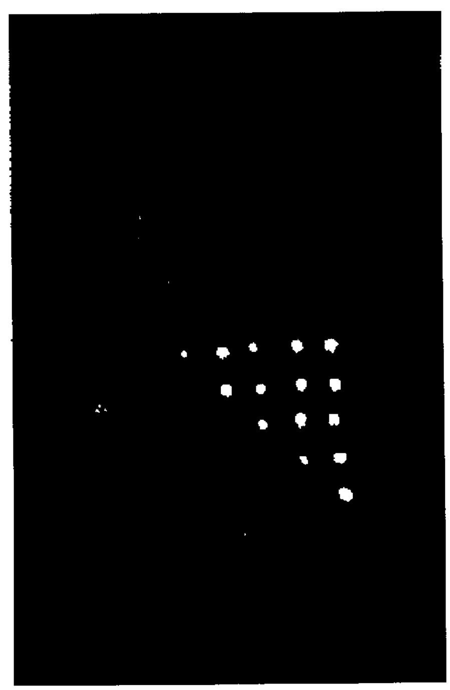


FIG. 8B.

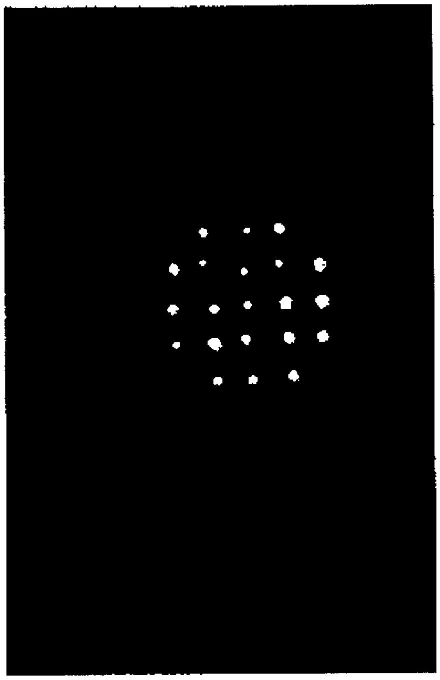


FIG. 8C.

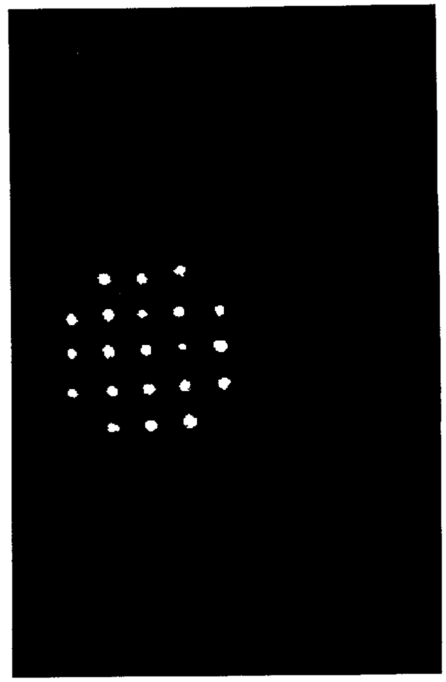


FIG. 8D.

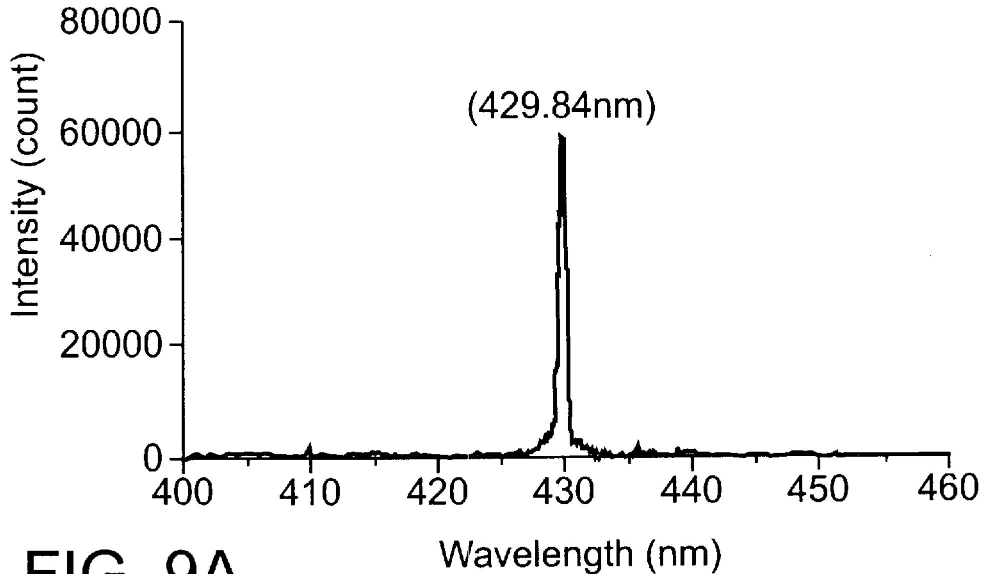

80000
60000
40000
20000
0
Intensity (count)
(429.84nm)
400
410
420
430
440
450
460
Wavelength (nm)

FIG. 9A.

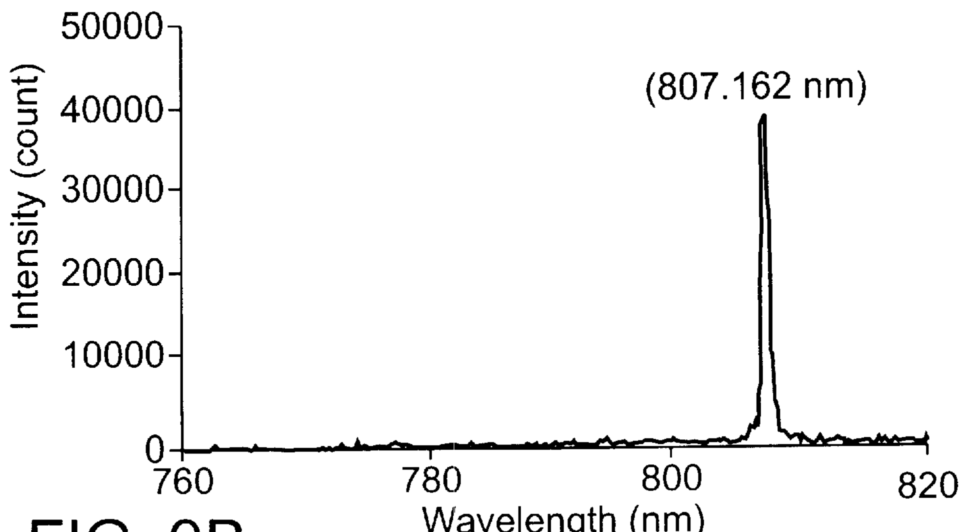

50000
40000
30000
20000
10000
0
Intensity (count)
(807.162 nm)
760
780
800
820
Wavelength (nm)

FIG. 9B.

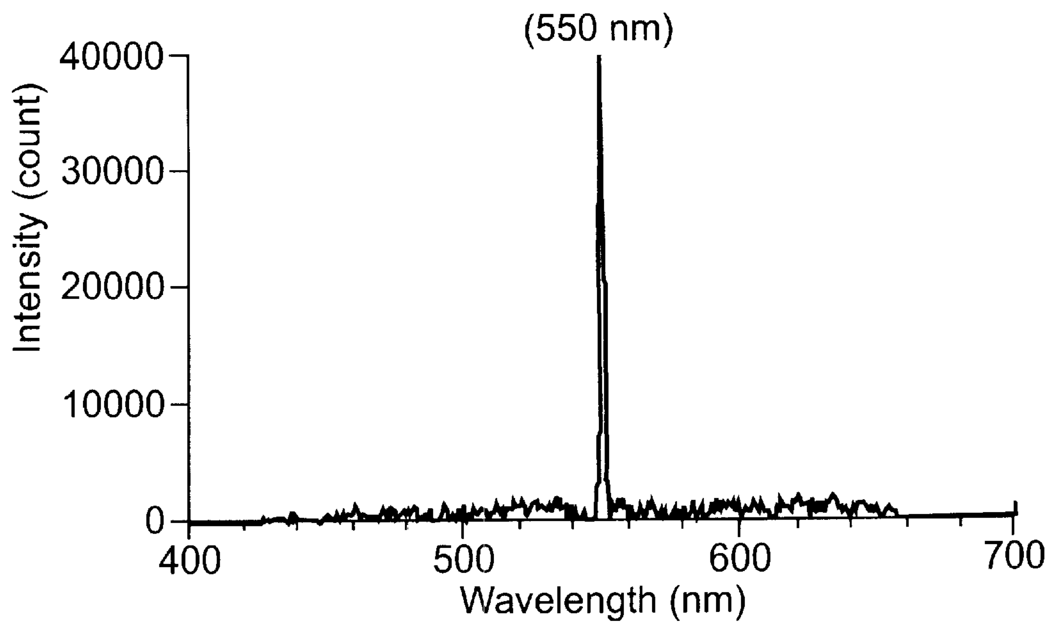

(550 nm)
Intensity (count)
40000
30000
20000
10000
0
400
500
600
700
Wavelength (nm)

FIG. 10.

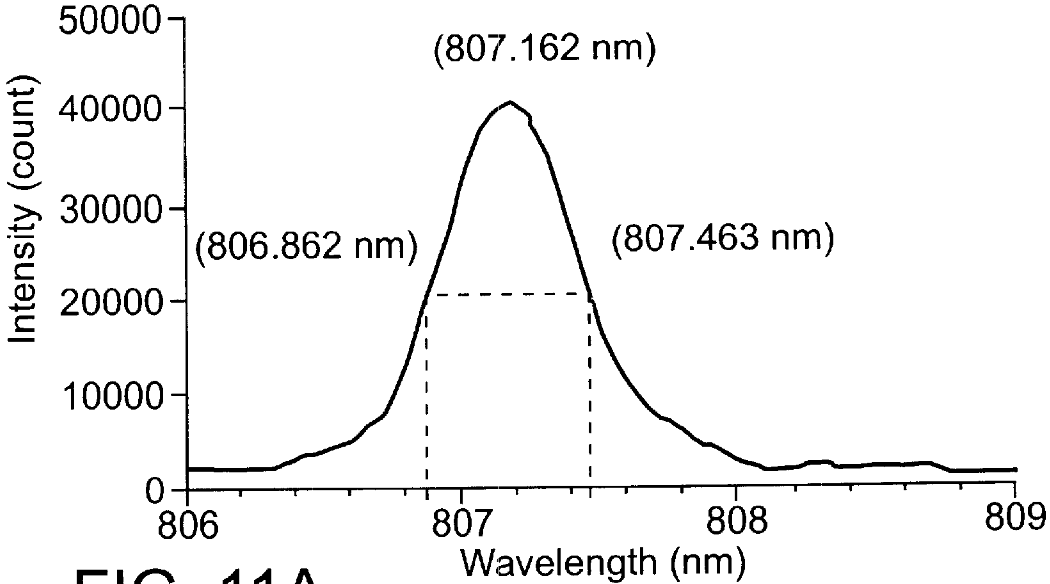


FIG. 11A.

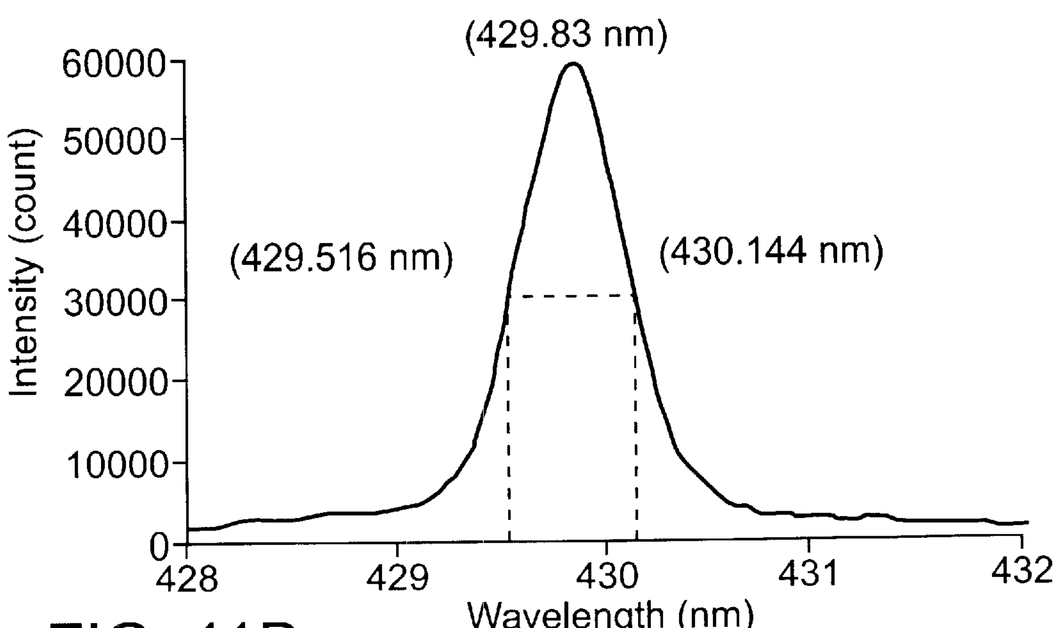


FIG. 11B.

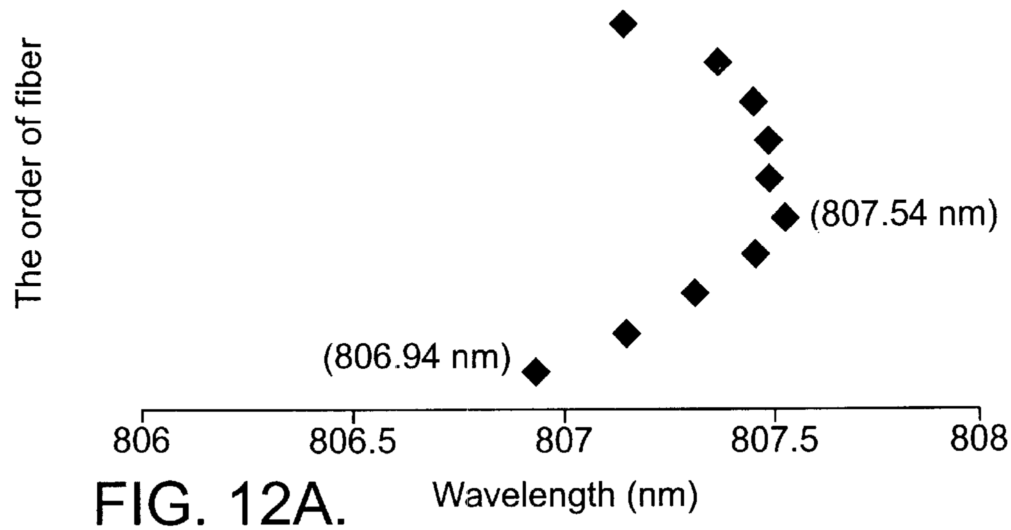


FIG. 12A.

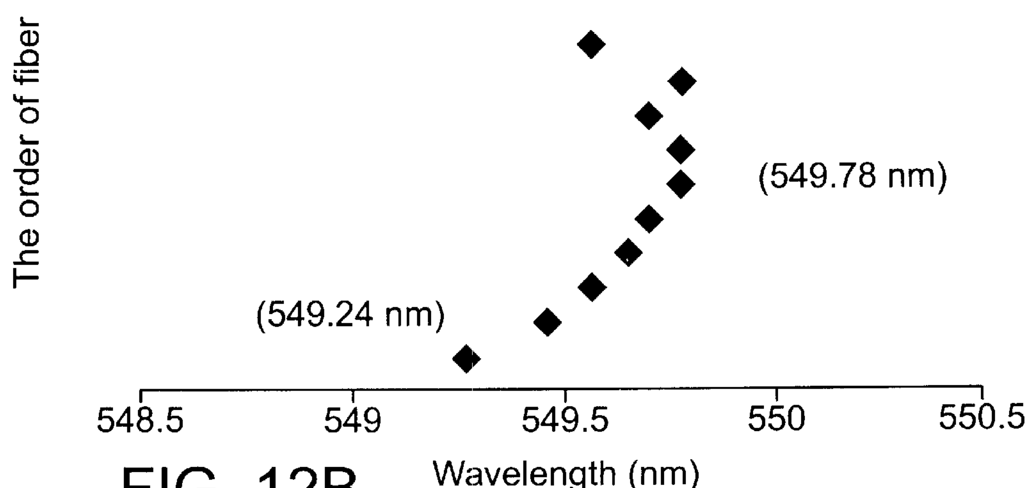


FIG. 12B.

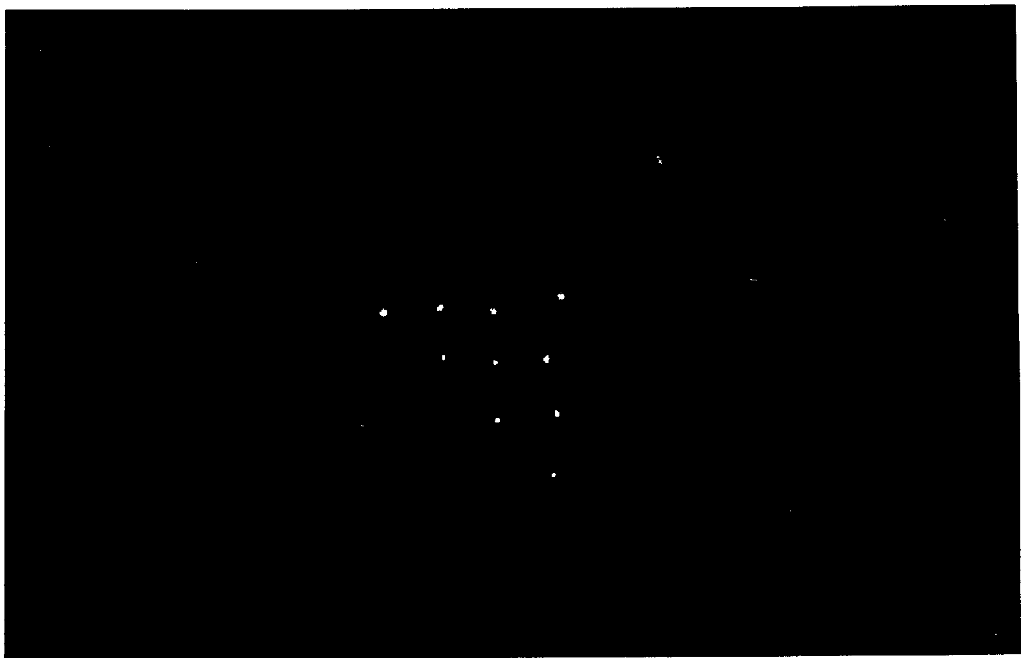


FIG. 13A.

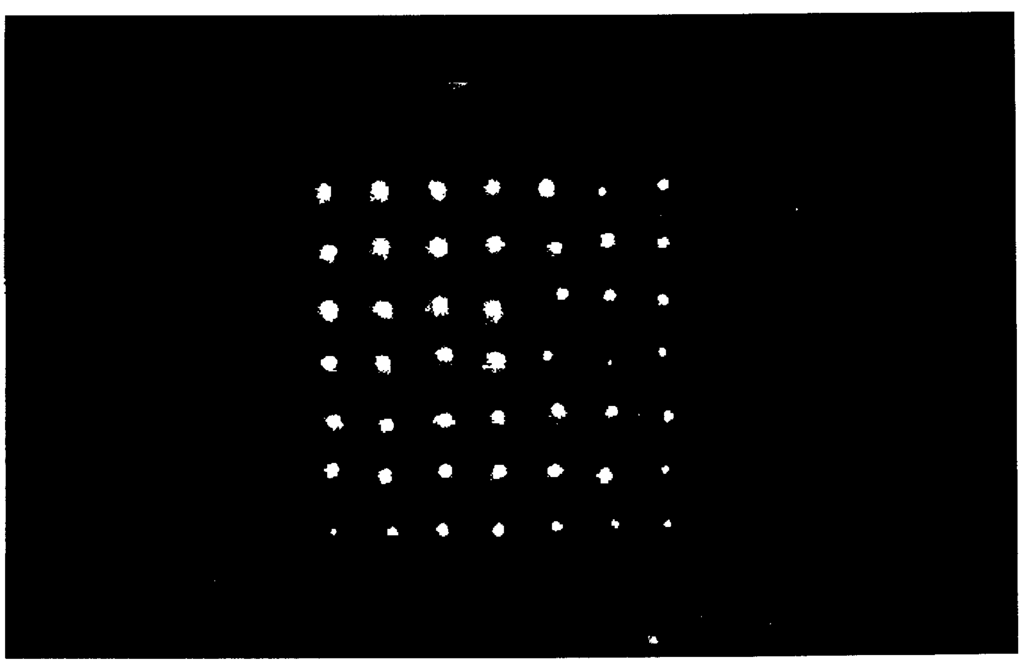


FIG. 13B.

TWO-DIMENSIONAL OPTICAL FILTER AND ASSOCIATED METHODS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to provisional application No. 60/237,813, filed Oct. 4, 2000, entitled "Two-Dimensional Optical Filter with High Spectral, Temporal, and Spatial Resolution."

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to two-dimensional optical filters and methods, and, more particularly, to such devices and methods having high spectral resolution and being adapted for continuous tuning.

2. Description of Related Art

The spectral filtering of multicolor images has been studied [1], resulting in filters employing absorption [2–7], dispersion [7–11], selective reflection [12–15], and spectrally selective transmission [1, 16–22]. A variety of techniques are known for spectral image filtering [23], including dichroic coated filters [24–27], holographic filters [28–35], acousto-optic tunable filters [35], Fabry-Perot tunable filters [24, 35–39], tunable birefringent filters [23, 40–46], and Lyot filters [23, 43–47]. The filtration mechanisms vary from the use of Bragg diffraction caused by periodically modulated refractive indices in holographic and acousto-optic tunable filters to the use of selectivity in transmission by polarization in Lyot filters. The basic underlying objective is the selective transmission, absorption, or reflection of a selected optical range. These techniques and their development for enhancing tunability and spectral sensitivity have been ongoing for some time [50–52].

High-sensitivity charge-coupled-device (CCD) cameras can be combined with notch filters for high-spectral-resolution two-dimensional imaging or with bandpass filters for broadband imaging. However, the dual requirements of fidelity of two-dimensional spatial imaging and high-resolution, continuous spectral tunability are not known to be available in currently existing systems.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an optical filter adapted to separate a multifrequency, two-dimensional image into spectral components.

It is an additional object to provide such a filter that retains the integrity of the two-dimensional image.

It is a further object to provide a method for making such a filter.

It is another object to provide a method for using such a filter.

These objects and others are attained by the present invention, an optical filter system for separating an image into spectral components. The filter comprises a plurality of input optical fibers, each having a first end and a second end. The first ends are two-dimensionally arrayed and are thus substantially coplanar; the second ends are substantially linearly arrayed and are thus also substantially coplanar. Each input fiber is configured to receive a portion of a two-dimensional input image at the first end and transmit the image portion to the second end.

A spectrally dispersive element following the input fiber array is configured to receive the image portions from the input fiber second ends and to output separated spectral components thereof.

A plurality of output optical fibers each has a first end and a second end. The first ends are substantially linearly arrayed and thus are substantially coplanar; the second ends are two-dimensionally arrayed and are also thus substantially coplanar. Each output fiber is configured to receive a portion of the output of the spectrally dispersive element at the first end and transmit the image portion to the second end. Further, the second ends are arrayed in corresponding fashion to the first ends of the input fibers for spatially reconstructing the input image.

The features that characterize the invention, both as to organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description used in conjunction with the accompanying drawing. It is to be expressly understood that the drawing is for the purpose of illustration and description and is not intended as a definition of the limits of the invention. These and other objects attained, and advantages offered, by the present invention will become more fully apparent as the description that now follows is read in conjunction with the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of the optical filter of the present invention.

FIG. **2** is a schematic diagram of the filter system.

FIG. **3** illustrates the pathways of the fibers in the input and output arrays.

FIG. **4** is a perspective view of a device for aligning the one-dimensional fiber array.

FIG. **5** is an output image for He—Ne laser illumination.

FIG. **6** illustrates potential areas of cross-talk in adjacent fibers.

FIG. **7** shows a cross-talk check.

FIGS. **8**A–**8**D illustrate two input images in two different positions: (**8**A,**8**B) a triangle; (**8**C,**8**D), a circle.

FIGS. **9**A, **9**B illustrate the wavelength range of the system, with FIG. **9**A showing the short-wavelength range and FIG. **9**B, the long-wavelength range.

FIG. **10** is a result of a spectral leakage check.

FIGS. **11**A, **11**B illustrate a bandwidth measurement at (FIG. **11**A) the short-wavelength range and (FIG. **11**B) the long-wavelength range.

FIGS. **12**A, **12**B tests for spectrum uniformity at (FIG. **12**A) 807.25 nm and (FIG. **12**B) 549.5 nm.

FIGS. **13**A, **13**B show the ability of the system to perform pattern recognition based on spectral signature at (FIG. **13**A) 450 nm and (FIG. **13**B) 458 nm.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

A description of one embodiment of the present invention will now be presented with reference to FIGS. **1**–**13**B. The optical filter uses optical fiber bundles to maintain image integrity while accurately redirecting the spectral components after separation by a diffraction grating. With a suitably arranged fiber array, the image can be angularly and spatially separated without overlap in order to output a two-dimensional image at a desired wavelength.

The System

A block diagram of the system **10** of the present invention is given in FIG. **1**, with a schematic in FIG. **2**. A two-

dimensional input image **12** impinges on an input optical fiber array **14**. Prior to entering the array **14** there may be placed, if desired, an optical element **16** to achieve magnification (for higher-spatial-resolution imaging) or reduction (for greater field-of-view imaging).

The input array, or input fiber bundle, **14** comprises a plurality of optical fibers **140**, each having a first end **141** and a second end **142**. The arrangement of the fibers **140** depends upon the desired application, with a close-packed orientation being preferred for highest resolution and a more scattered, or loose-packed, orientation preferred for site-specific multipoint imaging. Thus the invention is not intended to be limited to a particular packing embodiment.

Preferably the fibers' first ends **141** should be substantially coplanar for receiving the input image. The input array **14** digitizes the input image, with the spatial resolution thereof depending upon the resolution of the digitization process, which is determined by such characteristics as fiber diameter and packing density. As an example, 10-μm single-mode fibers with interfiber spacings <20 μm provides high spatial resolution. Further, if the image is magnified prior to entering the input array **14**, a spatial resolution of <1 μm is achievable.

The second ends **142** of the input array **14** are oriented into a linear array to provide a linear image for subsequent spectral filtering (see FIG. **3**). In a preferred embodiment of the invention, adjacent fibers **140** in the linear array are connected at the two-dimensional first ends **141** to spatially contiguous regions. This sequencing of fibers **140** reduces errors in spatial fidelity in the output spectral image.

The optical image of the input array **14** at the one-dimensional second end **142** next becomes the object for a spectrally dispersive element **18**, such as, but not intended to be limited to, a monochromator, for dispersing the constituent spectral components. A monochromator may be used as a dispersing element when the slit width is wider than the fiber diameter and as a spectral filter when the slit width is narrower than the fiber diameter. Preferably the one-dimensional input image is imaged at a 1:1 ratio at the output of the filter **18**. The narrow width of the second end **142** of the input array **14**, which constitutes, in effect, the width of the input slit of the filter **18**, coupled with the achievable spectral dispersion of a typical triple-grating monochromator, permits angstrom-level resolution of the output spectral image.

An output optical fiber array **20** is configured substantially identically to the input array **14**. Now the one-dimensional fiber array comprises the first ends **201** of the component fibers **200** and constitutes the output slit of the filter **18**. By adjusting the grating **180** of the filter **18**, a desired spectral component of the linear image can be obtained on the output array **20**. The tunable spectral dispersion analyzes the input light into its spectral components and permits a selection of a desired individual frequency component of the initial multicolor image while maintaining the spatial integrity of the linear input image.

Imaging the output of the spectrally dispersive element **18** onto a substantially identical one-dimensional fiber array **20** provides a one-to-one correlation between the spatial information contained in the two linear arrays **14, 20**. Light from each fiber **140** in the input array **14** to the filter **18** is filtered, with the results of the filtration obtained in the corresponding spatial counterpart fiber **200** of the output array **20**.

Since light at the spatial location of each fiber **200** of the output array **20** can be traced back to a corresponding origin **140** in the input array **14** prior to filtering, the second ends **202** of the fibers **200** of the output array **20** can be reconstituted into the same configuration as the original two-dimensional array to obtain a spectrally filtered, two-dimensional image of the original object at a desired wavelength.

The final image can be detected using, for example, a CCD camera **22**, and then displayed, for example, in real time on a video monitor **24**. Exemplary modes of detection include:

1. If the original object is a dynamically evolving entity, such as fluorescence from an expanding laser-ablated plume, a fast, time-gated camera, such as an intensified charge-coupled device (ICCD) camera, can be used to capture transient two-dimensional spectral images. At present, commercially available gate widths for such cameras permit attainable temporal resolutions for such dynamic images in the 10-ns range.
2. Another mode of detection comprises time-integrated detection of images for which dynamic characteristics are not required. Fast gating is not required for this mode, which is suitable, for example, for objects having extremely low light intensities.

The exemplary system schematic of FIG. **2** illustrates a two-dimensional object image **12** incident on the input array **14** and thereby digitized into a plurality of pixels. The light emerging from the second ends **142** is collected by a first concave mirror **25** and sent to a grating **180** as a collimated parallel beam. The first-order diffraction from the grating **180** is incident on a second concave mirror **26**. The image of the input one-dimensional array **14** is formed in the focal plane at a predetermined distance, here 12 in., away from the second mirror **26** and comprises a ribbon of color comprising a series of horizontal colored lines.

In each horizontal line, representing the image of a single pixel, the color varies from blue to red from one end to the other for an incident white light object image. Each color line in the ribbon is therefore the image of a corresponding fiber **140** in the one-dimensional end **141** of the input array **14**. The one-dimensional end **201** of the output array **20** is vertically aligned on a desired spectral region of the band, for collecting light from the corresponding fibers **140** in the input array **14**. The image is then restored to its two-dimensional form at the two-dimensional end **202** of the output array **20**.

In the exemplary embodiment shown in FIG. **2**, the filter **18** comprises a monochromator comprising a single square, plane reflection grating 1×1 in., having 1200 grooves/mm. The grating **180** of filter **18** is mounted on a stage **181** to achieve vertical positioning of the grooves and permit three degrees of freedom of movement, including horizontal and vertical adjustments and vertical rotation. The zeroth order of diffraction from the grating **180**, while having the greatest intensity, is not usable, as there is no angular separation between the spectral components of the image. In this embodiment only the first-order diffraction was collected by the concave mirror **26**.

Both mirrors **25, 26** comprise front-reflection concave mirrors having a 6-in. diameter and a 12-in. focal length. Mirrors are believed preferable over a lens-based system in their elimination of chromatic aberration. The first mirror **25** is positioned 12 in. away from the one-dimensional end of the input array **14**; the second mirror **26**, 12 in. away from the one-dimensional end of the output array **20**. Thus the two mirrors **25, 26** form a telescope of unit magnification in effect. This arrangement ensures that the beams incident on the grating are parallel beams and allows accurate one-to-one imaging between the one-dimensional array ends. The spectrum from the grating **180** avoids interfiber spatial and

spectral overlap, thereby ensuring the smallest bandwidth and lowest cross-talk for the system **10**.

The image is then collected by the detector **22**, which may comprise a gated CCD camera or optical multichannel analyzer (OMA) system as desired or appropriate.

The Fiber Arrays and Their Fabrication

In a preferred embodiment the input **14** and output **20** fiber arrays should be substantially identical. The two-dimensional ends comprise a 10×10 fiber array; the one-dimensional ends **142**, **201**, a 100×1 array (FIG. **3**). In one embodiment, each fiber **140**, **200** comprises silica and has a 200-μm core diameter and a 240-μm total diameter including the cladding. The arrays **14**, **20** each have a length of 24 mm at the one-dimensional end, and each fiber **140**, **200** has a length of 40 cm.

The transmission range of the fibers spans the visible and infrared region, 400–1200 nm. The fiber ends are polished to a surface roughness better than 1 μm.

The imaging arrangement necessitates that the one-dimensional structures are the same spatially, including the same microarrangement and spacing of each individual fiber end. Otherwise, a fiber in the output one-dimensional end **201** would not be able to collect the light from its corresponding counterpart in the input one-dimensional end **142** of the fiber array or not be able to collect light at a desired wavelength.

The two fiber arrays **14**, **20** in this embodiment are formed in this exemplary embodiment using 100 fibers, each 80 cm in length. Using the device shown in FIG. **4**, two fibers **31**, **32** are glued in parallel fashion onto a glass slide **30**. Two pieces of glass **33**, **34** are glued atop the fibers **31**, **32**, creating a slot **35**. The desired 100 fibers are then inserted into the slot **35** next to each other, and the fibers and glass slide **30** are glued together, for example, with an epoxy-type glue. After the glue is dry, the assembly is cut apart along the dotted line **36** with a diamond saw. Both cut ends of each bundle are finally mechanically polished.

The two-dimensional ends **141**, **202** of the arrays **14**, **20** are formed using specially designed fiber holders. Two plastic disks, having diameters of 24 mm and thicknesses of 0.25 in., each have 100 holes drilled therein in a 10×10 square array, each hole having a 508-μm diameter, with a center-to-center distance of 2 mm between consecutive holes.

A 1.375-in.-long hypodermic needle having an inner diameter of 250 μm is inserted and glued into each of the 200 holes to provide support for the fibers. The disks are fitted and glued inside glass tubes. The fibers are inserted into the needles by pushing on all the fiber ends with, for example, a flat microslide to ensure coplanarity of the ends. Then mounting wax is used to fix the fibers in position to form the two-dimensional arrays. It may be appreciated by one skilled in the art that additional methods may be contemplated, including different techniques and materials to achieve the same fiber arrays described herein.

System Characterization

Testing of the system **10** was performed using two kinds of light sources. A He—Ne laser had monochromaticity and directionality to permit ease of alignment and calibration.

In order to verify a one-to-one correspondence between the arrays **14**, **20**, the two-dimensional ends **141** of the input array **14** were illuminated by a lens-expanded beam of laser light at 632.28 nm, with the output image from the output array **20** monitored with a CCD camera (FIG. **5**). The tilt of the illustrated image is because of a tilt of the camera. Variations in the spatial intensity profile are due to variations in laser beam intensity at the input end. It was found that misalignments at fiber numbers **57**, **68**, and **77** were caused by mispositioning of the fibers during fabrication, and that fiber number **100** (lower right-hand corner) was broken. However, all fibers were illuminated on tuning the grating to the proper laser wavelength. Even a slight detuning extinguished the illumination substantially completely.

The spatial integrity of the two-dimensional image after transmission through the filter is an important issue. For example, if the image at each input one-dimensional end is larger than the actual size of the output one-dimensional array end (FIG. **6**), it is possible for the light from one input fiber **140** to "leak" into other adjacent fibers, which is referred to as spatial cross-talk. This could manifest itself in spatial as well as spectral diffusion and resultant distortion of the transmitted image.

The structure of the fiber array (FIG. **3**) places fibers number **1**–**10** are in order horizontally, as are fibers **11**–**20**, etc. An exemplary check of cross-talk is shown in FIG. **7**, with the column **149** of FIG. **3**, comprising fibers **2**, **12**, **22**, . . . , **92**, illuminated exclusively. It can be seen that no illumination of adjacent columns was detected, which was also the result for all other columns and all rows. This is particularly significant for the close-packed fiber arrays **14**, **20** of the present system **10**.

Restoration of an input image was checked to ensure that the arrays properly rearrange the pixels following transformation into a one-dimensional array. Two shapes, a triangle and a circle, positioned in two locations, were input, with the results shown in FIGS. **8A**–**8D**. In this test, the fibers were more sparsely arranged, with a 2-mm center-to-center distance, determining a lower resolution of the output image.

The spectral response of the system **10** was also tested using broadband illumination from a xenon arc lamp, emitting in the 50–1500-nm range. The lamp illuminated the input array **14**, and an OMA detector was placed at the output array **20**, with angle tuning of the grating **180** allowing output frequency selectivity of the two-dimensional image. Two examples at 430 and 807 nm (FIGS. **9A** and **9B**) show continuous tunability, with the system range limited only by the wavelength the fiber can transmit, here 400–1200 nm.

When the system **10** is tuned to a specific wavelength, other wavelengths should be efficiently rejected in the output, and this lack of "spectral leakage" is demonstrated in FIG. **10**. Tuning the system **10** to a wavelength in the green region (λ=550 nm), for example, and scanning from 400 to 700 nm, covering most of the visible spectrum, leads to no evidence of emission at other wavelengths. This was verified at other transmission wavelengths as well.

The transmission bandwidth can be obtained by high-resolution measurements of a spectral line detected by the OMA. FIGS. **11A** and **11B** show the bandwidth of the spectra depicted in FIGS. **9A** and **9B**, respectively. The bandwidths (FWHM) for both short- and long-wavelength ranges are approximately 0.6 nm, indicating a very uniform bandwidth throughout the tunable range. The theoretical bandwidth, on the basis of the resolution of the diffraction grating and the diameter and position of the fibers used in the one-dimensional output array **20**, is calculated to be 0.66 nm, which is consistent with the experimentally observed values. This calculated value for bandwidth is obtained by considering the ratio of the spatial spread of the wavelength range in the plane of the band to the core diameter of the output one-dimensional fiber.

If the position of a fiber in any of the one-dimensional arrays is off slightly relative to other fibers, the wavelength selected will be different from that expected. The OMA was

used to test fibers in column **5** for spectral uniformity along the fiber array. By choosing fibers in a column, it is ensured that fibers are sampled that are evenly spaced in the one-dimensional array (see FIG. **3**). Further, sampling any entire column affords data over a large range of the one-dimensional array and is thus truly representative of the maximum extent of the spectral nonuniformity. The wavelength of the peak value from each fiber was recorded fiber by fiber and are plotted in FIGS. **12**A and **12**B, where a curvature is evident. The largest deviations in wavelength throughout the entire range are, respectively, 0.6 and 0.54 nm. This maximum variation is, however, within the 0.6-nm bandwidth discussed previously. Similar results have been obtained for fibers in other columns.

The observed curvature is due to off-axis reflections from the concave mirror. If the system **10** filters a single-frequency light source, such as the output of a He—Ne laser, the images of the first one-dimensional array **14** have a slight spatial curvature introduced by the off-axis fibers. As a result, the second one-dimensional array **20** will pick up slightly disparate wavelengths in a multiwavelength spectrum. Interestingly, from FIGS. **12**A and **12**B, the positions of the points are not random; rather, they tend to form a smooth curve. This provides a remedy for alleviating this slight problem of spectral nonuniformity. The solution is to match the spatial arrangement of the second one-dimensional array according to the curvature of the imaging mirror, so that all the fibers can image the exact wavelength selected, thereby resulting in better spectral uniformity.

An important function of the filter system **10** is to allow spatial patterns of a selected wavelength to pass through. In order to test this function, two object images were projected onto the input of the system simultaneously. One of these objects was a triangle at a wavelength of 450 nm, while the other was rectangular at a wavelength of 458 nm. The wavelengths were generated by an Ar ion laser (458 nm) and a Xe arc lamp with a commercial filter of 450 nm. By appropriately tuning the angle of the grating **18**, only the desired pattern can be selected at the output of the system **10** and recorded by a CCD camera (FIGS. **13**A and **13**B). There is no observable interference between the images at these two different but closely spaced wavelengths. In both cases the output of the system **10** was identical to the shape and size of the corresponding spectral component in the dual-wavelength input object.

These performance tests confirm the capability of a system as described herein to analyze a two-dimensional multiwavelength object into its spectral constituents, with a potential wavelength resolution on the order of angstroms and micrometer or better spatial resolution. Gated viewing can provide the derivation of constituent monochromatic, two-dimensional images with temporal resolution of dynamic events on the 10-ns time scale. The two-dimensional spectral imager is continuously tunable, and any wavelength that can be transmitted by the optical fibers and dispersed by the monochromator is available for viewing.

Numerous applications exist in the viewing of two-dimensional objects, in which the ability to view different spectral components while maintaining spatial integrity is important. For example, CCD imaging has been used to image laser-ablated plume dynamics by viewing the plume fluorescence [53–56]. The filter of the present invention is particularly suitable for studying plume emission during the laser ablation process for the growth of thin films. It is also possible to provide species-resolved, dynamic information about the spatial expansion and propagation of individual atomic and molecular species in a multicomponent laser-ablated plume. This is believed possible, as the demonstrated resolution and tunability of the spectral imager allows the isolation of emission from any atomic or molecular species and two-dimensional display in real time.

Other applications include, but are not intended to be limited to, plasma diagnostics, combustion diagnostics (such as rocket plume imaging), real-time process monitoring for fluorescent processes, medical imaging (for example, the fluorescent detection of cancer cells), and sensing of spatial temperature variations (via blackbody radiation detection using a suitable fiber material).

It may be appreciated by one skilled in the art that additional embodiments may be contemplated, including different components and materials to achieve the same functionalities described herein.

In the foregoing description, certain terms have been used for brevity, clarity, and understanding, but no unnecessary limitations are to be implied therefrom beyond the requirements of the prior art, because such words are used for description purposes herein and are intended to be broadly construed. Moreover, the embodiments of the apparatus illustrated and described herein are by way of example, and the scope of the invention is not limited to the exact details of construction.

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What is claimed is:

1. An optical filter comprising:

a plurality of input optical fibers, each input optical fiber having a first end and a second end opposed to the first end, wherein:

the first ends are substantially two-dimensionally arrayed;

the second ends are substantially linearly arrayed; and

each input fiber is configured to receive a portion of a two-dimensional input image at the first end and transmit the image portion to the second end;

a spectrally dispersive element for receiving the image portions from the input fiber second ends and for outputting separated spectral components thereof; and

a plurality of output optical fibers, each having a first end and a second end opposed to the first end, wherein:

the first ends are substantially linearly arrayed;

the second ends are substantially two-dimensionally arrayed;

each output fiber is configured to receive a predetermined portion of the spectrally dispersed output at the first end and transmit the image portion to the second end; and

the second ends are arrayed in corresponding fashion to the first ends of the input fibers for spatially reconstructing the input image.

2. The optical filter recited in claim **1**, wherein the plurality of input optical fibers are positioned relative to each other in a predetermined packing arrangement commensurate with a desired resolution.

3. The optical filter recited in claim **2**, wherein the positioning of the input optical fibers comprises a close-packed arrangement for maximum resolution.

4. The optical filter recited in claim **2**, wherein the positioning of the input optical fibers comprises a loose-packed arrangement for site-specific multipoint imaging.

5. The optical filter recited in claim **1**, wherein each input fiber has a diameter selected for achieving a desired resolution.

6. The optical filter recited in claim **1**, wherein the spectrally dispersive element comprises a monochromator for dispersing constituent spectral components of the input image.

7. The optical filter recited in claim **6**, wherein the monochromator comprises a triple-grating monochromator.

8. The optical filter recited in claim **6**, wherein the spectral component output comprises a 1:1 ratio with the input image.

9. The optical filter recited in claim **1**, wherein the spectrally dispersive element comprises a grating, and the optical filter further comprises:

a first concave mirror upstream of the grating for forming a collimated parallel beam from the output of the second ends of the input fibers; and

a second concave mirror positioned for collecting diffraction from the grating and for forming an image of the output of the second ends of the input fibers at a focal plane.

10. The optical filter recited in claim **9**, further comprising a stage for mounting the grating thereon, the stage comprising means for adjustment in a vertical direction, in a horizontal direction, and rotationally about a vertical axis.

11. The optical filter recited in claim **9**, wherein the second concave mirror is positioned for collecting a first order of diffraction from the grating.

12. The optical filter recited in claim **1**, wherein the input fibers and the output fibers are substantially identical.

13. The optical filter recited in claim **12**, wherein each input fiber and each optical fiber comprises a silica fiber and a cladding surrounding the silica fiber.

14. The optical filter recited in claim **12**, wherein each fiber has a transmission range spanning the visible and infrared region of the optical spectrum.

15. The optical filter recited in claim **1**, wherein the spectrally dispersive element is continuously tunable.

16. The optical filter recited in claim **1**, wherein the first end of the output fibers is continuously translatable to select a predetermined spectral component of a dispersed image.

17. A system for optically filtering an input image comprising:

a plurality of input optical fibers, each input optical fiber having a first end and a second end opposed to the first end, wherein:

the first ends are substantially two-dimensionally arrayed;

the second ends are substantially linearly arrayed; and

each input fiber is configured to receive a portion of a two-dimensional input image at the first end and transmit the image portion to the second end;

a spectrally dispersive element for receiving the image portions from the input fiber second ends and for outputting separated spectral components thereof;

a plurality of output optical fibers, each having a first end and a second end opposed to the first end, wherein:

the first ends are substantially linearly arrayed;

the second ends are substantially two-dimensionally arrayed;

each output fiber is configured to receive a predetermined portion of the spectrally dispersed output at the first end and transmit the image portion to the second end; and

the second ends are arrayed in corresponding fashion to the first ends of the input fibers for spatially reconstructing the input image into a final image; and

means for detecting the final image.

18. The system recited in claim **17**, further comprising an optical element for altering a size of the input image upstream of the input fiber bundle.

19. The system recited in claim **18**, wherein the optical element is selected from a group consisting of a magnification element and a reduction element.

20. The system recited in claim **17**, wherein the detecting means comprises a camera.

21. The system recited in claim **20**, wherein the camera comprises a charge-coupled-device camera.

22. The system recited in claim **20**, wherein the camera comprises a fast, time-gated camera.

23. The system recited in claim **20**, wherein the camera comprises a time-integrating camera.

24. The system recited in claim **17**, further comprising means for displaying the final image.

25. The system recited in claim **24**, wherein the display means comprises a video monitor.

26. The system recited in claim **17**, wherein the spectrally dispersive element comprises a monochromator for dispersing constituent spectral components of the input image.

27. The system recited in claim **17**, wherein the spectrally dispersive element comprises a grating, and further comprising:

a first concave mirror upstream of the grating for forming a collimated parallel beam from the output of the second ends of the input fibers; and

a second concave mirror positioned for collecting diffraction from the grating and for forming an image of the output of the second ends of the input fibers at a focal plane.

28. The system recited in claim **27**, further comprising a stage for mounting the grating thereon, the stage comprising means for adjustment in a vertical direction, in a horizontal direction, and rotationally about a vertical axis.

29. The system recited in claim **17**, wherein each of the input fibers and the output fibers has a transmission range spanning the visible and infrared region of the optical spectrum.

30. The system recited in claim **17**, wherein the spectrally dispersive element is continuously tunable.

31. The system recited in claim **17**, wherein the first end of the output fibers is continuously translatable to select a predetermined spectral component of a dispersed image.

32. A method for filtering a two-dimensional optical image comprising the steps of:

directing a two-dimensional input image onto first ends of a plurality of input optical fibers, the input fiber first ends substantially two-dimensionally arrayed;

spectrally dispersing image portions from second ends of the input fibers, the input fiber second ends opposed to the first ends and substantially linearly arrayed; and

directing a predetermined portion of the spectrally dispersed image portions onto first ends of a plurality of output optical fibers, the output fiber first ends substantially linearly arrayed, the output fibers each having a second end opposed to the first end, the second ends substantially two-dimensionally arrayed in corresponding fashion to the first ends of the input fibers for spatially reconstructing the input image.

33. The method recited in claim **32**, wherein the spectrally dispersing step comprises using a monochromator to disperse constituent spectral components of the input image.

34. The method recited in claim **32**, wherein the spectrally dispersing step comprises using a grating, and further comprising the steps of:

forming a collimated parallel beam from the output of the second ends of the input fibers; and

collecting diffraction from the grating and forming an image of the output of the second ends of the input fibers at a focal plane.

35. The method recited in claim **34**, further comprising mounting the grating on a stage for adjusting a position of the grating in a vertical direction, in a horizontal direction, and rotationally about a vertical axis.

36. The method recited in claim **32**, wherein the spectrally dispersing step comprises providing means for continuously tuning the image portions from the input fiber second ends.

37. The method recited in claim **32**, wherein the directing step comprises providing means for continuously translating the output fiber first ends to select a predetermined spectral component of the spectrally dispersed image.

38. A method for optically filtering and detecting an input image comprising the steps of:

directing a two-dimensional input image onto first ends of a plurality of input optical fibers, the input fiber first ends substantially two-dimensionally arrayed;

spectrally dispersing image portions from second ends of the input fibers, the input fiber second ends opposed to the first ends and substantially linearly arrayed; and

directing predetermined portions of the spectrally dispersed image portions onto first ends of a plurality of output optical fibers, the output fiber first ends substantially linearly arrayed, the output fibers each having a second end opposed to the first end, the second ends substantially two-dimensionally arrayed in corresponding fashion to the first ends of the input fibers for spatially reconstructing the input image; and

detecting the final image.

39. The method recited in claim **38**, further comprising altering a size of the input image upstream of the input fiber bundle.

40. The method recited in claim **39**, wherein the altering step comprises one of the steps of magnifying and reducing the input image.

41. The method recited in claim **38**, wherein the detecting step comprises using a camera.

42. The method recited in claim **41**, wherein the camera comprises a charge-coupled-device camera.

43. The method recited in claim **38**, wherein the detecting step comprises time-gating the input image.

44. The method recited in claim **38**, wherein the detecting step comprises time-integrating the input image.

45. The method recited in claim **38**, further comprising displaying the final image.

46. The method recited in claim **38**, wherein the spectrally dispersing step comprises dispersing constituent spectral components of the input image using a monochromator.

47. The method recited in claim **38**, wherein the spectrally dispersing step comprises using a grating, and further comprising the steps of:

forming a collimated parallel beam from the output of the second ends of the input fibers; and

collecting diffraction from the grating and forming an image of the output of the second ends of the input fibers at a focal plane.

48. The method recited in claim **47**, further comprising mounting the grating on a stage for adjusting a position of the grating in a vertical direction, in a horizontal direction, and rotationally about a vertical axis.

49. The method recited in claim **38**, wherein the spectrally dispersing step comprises providing means for continuously tuning the image portions from the input fiber second ends.

50. The method recited in claim **38**, wherein the directing step comprises providing means for continuously translating the output fiber first ends to select a predetermined spectral component of the spectrally dispersed image.

51. The method recited in claim **38**, wherein each of the input fibers and the output fibers has a transmission range spanning the visible and infrared region of the optical spectrum.

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