Concept of a high-resolution miniature spectrometer using an integrated filter array

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A high-resolution miniature spectrometer has been demonstrated by utilizing a 128-channel integrated filter array, fabricated by using the combinatorial deposition technique, as a dispersive component whose pass-bands range from 722.0 to 880.0 nm with a bandwidth (or spectral resolution) from 1.7 to 3.8 nm and an average channel interval of 1.2 nm. The miniature spectrometer is smaller than 1 cm³ without any moving parts. This kind of miniature spectrometer has the advantages of very low payload, high resolution, and high reliability simultaneously, which are especially urgently needed for space applications. © 2007 Optical Society of America


Compact, lightweight, and rigid miniature spectrometers without moving parts are needed for a wide variety of applications, including space applications, where every inch of payload counts. Miniaturization increases the portability and paves the way for making in situ measurements. It also eases the integration of microspectrometers and miniature spectrometers into other technologies, such as microelectronics, and helps to realize lab-on-a-chip devices and very large scale integrated devices.1 Spectrometers in general can be classified as, for example, grating-based,2–7 Fourier-transform-based,8,9 tunable-filter-based,10,11 and wedge-filter-based12 spectrometers. Microspectrometers and miniature spectrometers have been built by using many technologies, such as microelectromechanical systems,7,11 CMOS,10 micro-optic electromechanical systems,12 and integrated optics technologies.2,14 With a single dimension of the optical part being about 1 or 2 cm, grating-based spectrometers have been demonstrated to give a resolution (FWHM) $\Delta \lambda$ of 5 nm (Ref. 15) over a 100 nm spectral range and 10 nm (Ref. 2) over a 300 nm spectral range in the visible. Two other grating-based visible and infrared microspectrometers with a single dimension of only a few millimeters have been demonstrated to give a FWHM of ~60 nm at 600 nm and ~500 nm at 5 μm, respectively.3 Recently, a miniature spectrometer with an optical part as small as 0.2 cm³ has been demonstrated with a resolution varying from 0.3 to 4.6 nm in the visible by controlling the CCD position.1 Apparently there is a trade-off among the size of the spectrometer, its spectral resolution, and its moving parts.

In this Letter we present the concept of a high-resolution miniature spectrometer using an integrated filter array as dispersive component. It is a vital component for such miniature spectrometers, which can be designed with high resolution and small size to match a detector array or CCD very well. A 128-channel integrated filter array fabricated by using the combinatorial deposition technique16 is combined with a CCD to form a miniature spectrometer smaller than 1 cm³ with a spectral resolution of 1.7–3.8 nm.

Although integrated filter arrays of small size and high resolution are vital components for high-resolution miniature spectrometers, they can hardly be fabricated by using conventional approaches. We have developed two high-efficiency approaches for the fabrication of integrated filter arrays. One is a combinatorial etching technique that introduces the combinatorial etching process into the traditional film deposition procedure.17–20 It involves making two deposits and running the etching process N times for a $2^N$ integrated filter array. The etching process may influence the properties of integrated filters when their bandwidth is ultranarrow. The other is a combinatorial deposition technique without any etching process. It needs only $N+2$ deposition processes for a filter array integrated with $2^N$ elements. The integrated filter array used in this Letter is fabricated by using the latter approach. It is a $8 \times 16$ filter array in the near infrared (NIR) region fabricated with only nine depositions. The detailed fabrication procedure has been reported elsewhere.16

The total size of the fabricated filter array is 12 mm × 12 mm, with a substrate thickness of 1 mm. Each filter element’s size is smaller than 1.5 mm × 0.75 mm. The filter elements’ size and the total size of the filter array can be made smaller by introducing photolithography into the fabrication procedure. The
spectra of all filter elements on the filter array, shown in Fig. 1(a), were measured by modified micro-Raman spectroscopy (Dilor LabRam-Infinity). The channels of the 128 filter elements range from 722.0 to 880.0 nm, corresponding to spectral range of 158 nm. In each row the eight elements are distributed linearly, and the whole trend is also linear, as shown in Fig. 1(b). The average channel interval is 1.2 nm. The bandwidth of the channels, or in other words the spectral resolution, ranges from 1.7 to 3.8 nm, corresponding to relative bandwidth ($\Delta\lambda/\lambda$) from 0.22% to 0.44%. More than 85% of the bandwidth is smaller than 0.3%. The results show that the channels of all the integrated filters are ultranarrow (relative bandwidth smaller than 1%) and provide a high resolution. The peak transmittance of the channels is between 21% and 65%. More than 65% of them are larger than 30%.

Thus such an integrated filter array can act as a dispersive component. It is small enough to match a CCD directly and form a compact spectrometer smaller than 1 cm$^3$ (12 mm $\times$ 12 mm $\times$ 5 mm). Figure 2 shows the schematic diagram of a compact spectrometer composed of our filter array and a CCD. The CCD used in this experiment is a SONY-ICX409AK. It is an interline CCD solid-state state image sensor with total pixel number of 795 $\times$ 596 and pixel size of 6.5 $\mu$m $\times$ 6.25 $\mu$m. The filter array is just put in front of the CCD, without any moving parts. Therefore the structure is very compact and stable. Every filter element matches a certain number of pixels of the CCD. Monochromatic light of different wavelengths will propagate through different filter elements and reach corresponding pixels of the CCD. When white light is incident on the filter array, monochromatic light of different wavelengths will propagate through different element locations. Then the CCD can collect the signals at different wavelengths and form a spectrum simultaneously and send it to a computer in real time. This kind of miniature spectrometer has the advantages of very low payload, high resolution, and very high reliability, which are especially urgently needed for space applications.

In a filter array type of dispersive component, monochromatic light that is incident on the filter array can only propagate through the place whose channel is closest to the light's wavelength. In Fig. 3 are two pictures of the 128-channel integrated filter array captured by a CCD when monochromatic light of 760 and 840 nm is incident on it. Only the light with a wavelength close to the channel of a filter element can propagate through that element.

Fig. 1. (a) Spectra of the 128-channel integrated filter array fabricated by using the combinatorial deposition technique, with an element size of 1.5 mm $\times$ 0.75 mm and total size of 12 mm $\times$ 12 mm. (b) Peak wavelength of each filter element.
est filter region are calibrated as the pixels for the corresponding wavelength. Therefore the CCD can simultaneously collect the signals at different wavelengths and form a spectrum in the range 722.0–880.0 nm.

To demonstrate the function of the miniature spectrometer utilizing our filter array, a filter sample was measured with both a conventional commercial spectrometer (Lambda900 UV-Vis-NIR Spectrometer) and our filter array spectrometer. The results are shown in Fig. 4. In Fig. 4(a), there are three peaks located at 779.5, 786, and 868 nm in the range of 720–880 nm measured by using the Lambda900 spectrometer. When measured with our filter array spectrometer, three peaks located at 781, 787, and 869 nm can also be clearly observed, and the spectral shape agrees very well with the result measured with the Lambda900 spectrometer, as shown in Fig. 4(b). The peaks at 781 and 787 nm, with an interval of only 6 nm, can be definitely distinguished. The shift of about 1 nm for all three peaks may result from the rough calibration of the filter array.

The above experimental results show that this kind of miniature spectrometer can be manufactured without any problem. However, misalignment may occur between the filter array and CCD or detector array, especially for filter arrays with a very small element size and large integration. In this case, some of the filter elements on the edge will match with fewer CCD pixels, resulting in weaker signals obtained by these channels and leading to a relatively low signal-to-noise ratio for these wavelengths in the spectrum. The tolerance to misalignment depends on the required signal-to-noise ratio of the spectrometer. One solution for this problem is to use a CCD with a size larger than the filter array to avoid some filter elements matching with fewer CCD pixels.

In this Letter the concept of a high-resolution miniature spectrometer has been presented by using an integrated filter array as dispersive component, which is a core component for such miniature spectrometers. The integrated filter array can be designed with high-resolution and a small size to match a detector array or CCD very well. A miniature spectrometer is demonstrated to be smaller than 1 cm³ with a spectral resolution in the range of 1.7–3.8 nm by combining a 128-channel integrated filter array with a CCD. Without any moving parts, such a miniature spectrometer simultaneously has the advantages of very low payload, high resolution, and very high reliability, which are especially urgently needed for space applications.

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References


Fig. 4. Spectra of a filter sample measured by both (a) a conventional Lambda900 UV-Vis-NIR Spectrometer and (b) our filter array spectrometer. They agree very well.