Invited Paper

Ultracompact Fully Integrated MegaPixel MultiSpectral Imager

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ABSTRACT

Multispectral imaging or imaging spectroscopy obtains spectral content of an object by dividing the image data, pixel by pixel, into wavelength (color) bands. The resulting 3D data cube (x, y, λ) allows materials to be identified by their pixel spectral content at multiple wavelengths in addition to their spatial characteristics. A new class of multispectral imaging systems are being developed that utilizes lithographically patterned dichroic filter arrays integrated with standard CCD and CMOS detector arrays. These new imagers offer the unique advantage of scalability to tens of Megapixel resolutions, compact size, and no moving parts. Our multispectral imagers are much simpler to manufacture in volume because the complexity is in the lithographically patterned dichroics rather than in the bulk optical system. The patterned dichroic filter arrays are fabricated utilizing standard microlithography techniques and can incorporate up to 10 different wavelength bands deposited onto a single substrate. Each channel is selectively patterned on the substrate with the dichroic filter coating applied using standard thin film coating techniques. The technique is repeated for all of the wavelength bands and then the final filter array is directly attached and aligned onto the CCD.

Keywords: Multispectral, Hyperspectral, Imaging, Spectral, Spectra, Patterned Dichroic, Filter Array, Bayer Pattern

1. INTRODUCTION

Multispectral imaging involves capturing images of a scene or object over multiple discrete wavelength bands and extracting spectral content from that data. By leveraging known spectral absorption or emission features to identify materials, the technique can be used for everything from mapping rock types in geological formations to identifying blood oxygenation or cancer cells. The problem is that multispectral imagers have historically been large, expensive, sophisticated airborne or satellite-mounted instruments. Because each scene is captured in three-dimensions (x, y, λ), the resultant data cubes can be gigabytes in size, while only a fraction of the data is useful. Even though multispectral imaging would be a beneficial tool for a range of low-cost, real-time, limited-wavelength applications like anticounterfeiting measures or medical diagnostics, the complexity of today's offering makes it impossible. This new lithographically patterned dichroic filter array approach presents a way to change that.

1.1 Traditional Multispectral and Hyperspectral Systems

There a very few commercially available multispectral imagers. Most multispectral systems tend to be one-off or research-based put together using off the shelf parts and cameras and can cost anywhere from tens of thousands to millions of dollars per system, depending on the application, wavelength bands, and resolution requirements. A typical multispectral imager essentially consists of either rotating filter wheels, mechanically diced thin-film dichroic filters mounted in front of an image sensor, or multiple cameras with bulk dichroic filters.

Even for those touted as commercial systems, there is no real volume production pathway with significant price or reduced complexity enhancements at even as few as tens or hundreds of units.

A majority of devices that yield multispectral data are in fact hyperspectral imagers that are set to a few different wavelength bands. In its most basic form, a hyperspectral imager consists of a wavelength dispersing element coupled to an image sensor. Most hyperspectral systems fall into one of the following categories; Whiskbroom/Pushbroom[1], or

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Tunable Filter[2,3]. In addition there are many different techniques being developed for multispectral imaging including lens arrays coupled to individual spectral filters[4], multiple bandpass filters on top of traditional color cameras[5] and Computed Tomography Imaging Spectrometers[6,7].

The most common, whiskbroom or pushbroom systems require the system to be flown over the landscape from above such as in an airplane or satellite to capture images of the swath of land below or to slide the object of interest beneath the system on a scanner such as a conveyer belt. The tunable filter system typically uses a 2-D CCD array and utilizes either liquid crystals or acousto-optical tunable filters (AOTFs) to scan the wavelength. All of these hyperspectral techniques have the advantage that they are able to image the scene at hundreds to thousands of spectral channels, each only several nanometers wide. To do so, they sacrifice either image spatial resolution or frame rate as they require increased acquisition time to scan either the scene or the spectrum. This increased acquisition time compromises and in some cases excludes using these systems when imaging dynamic phenomena or moving objects because they are not able to simultaneously capture the entire scene and all of the spectral content at once.

In addition even if the scene is not moving at all such as in a pathology slide, a hyperspectral imaging system generates a copious amount of digital data requiring significant acquisition and storage capabilities. Getting an answer from this data cube is computationally intensive and in many cases the complete hyperspectral data cube provides little additional information compared to just a few (typically 3-8) multispectral imaging bands. We have found that there are many applications where just a few wavelengths are “good enough.”

Using our lithographically patterned dichroic filter arrays, we can build multispectral imagers that capture a scene over a small number of spectral channels. More important, such filters can be fabricated quickly, economically, and reliably using well-established high volume batch-processing techniques.

1.2 The Bayer filter

The most commonly utilized approach to spectral imaging is an interlaced technique using three different colored filters placed on top of a 2-D detector array to produce a “color camera” via a technique called Bayer filtering.8 In a Bayer filter mosaic, each quartet of pixels utilizes absorptive gel filters for color selection. To match the human eye response one pixel filter transmits only red light, one pixel filter transmits only blue light, and two transmit only green light (see Figure 1). This filter overlays the image sensor pixels with one-to-one correlation; in other words, when the detector captures an image, 25% of the pixels capture red wavelengths, 25% capture blue wavelengths, and 50% capture green wavelengths. These RGB filters are typically absorptive gels and have extremely wide absorption bands with significant spectral cross talk between the red, green and blue channels. The resultant data is processed using color-space interpolation algorithms to create a color image.

We can apply this same architecture to our patterned multilayer dichroic optical filters. We begin with the Bayer filter concept but instead of using broad absorptive gels to capture data at red, green, and blue wavelengths, we custom design the dichroic filters so that the image sensor operates at λ1, λ2, λ3, and so on.

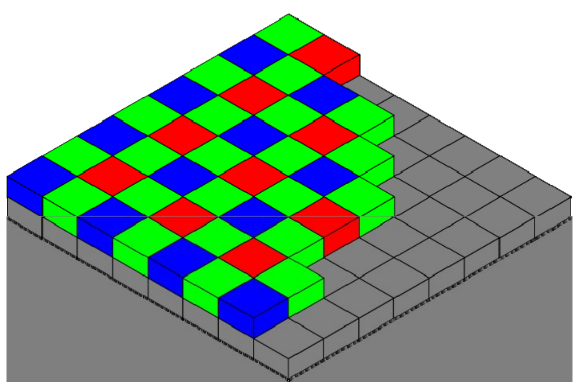


Figure 1. Bayer filter mosaics are a typical approach to color imaging in digital cameras.

2. PATTERNED DICHROIC FILTERS

The production of patterned filter array technology is based on the intersection of traditional thin film coating technology and standard semiconductor photolithography. It is common for optical processing technologies to utilize techniques and equipment from the domain of microelectronic fabrication.

Until recently, however, optical coatings have been one area that existed primarily in the macro realm; entire optical surfaces could be coated quite easily with a bandpass filter, for instance, but precise deposition of patterned optical filter coatings was limited by the use of metal masking. This masking could easily withstand the in-vacuum process heat needed to produce hard, durable dielectric multilayers, but was expensive to manufacture, difficult to align with the substrate, and unable to produce a deposited pattern that could be cleanly aligned "edge to edge" to existing patterns without gaps or overlapping. Similarly, the dicing and bonding of individual filters together to form an assembly is a tedious and expensive process at best, with miniaturization limited by handling and dicing constraints.

The dichroic filter array production technique combines modern optical thin film deposition techniques and standard microlithographic procedures, which enables the precision placement and patterning of optical thin film coatings on a single substrate. This process allows for multiple patterned arrays of different optical filters for the patterned sensors and multispectral imaging applications. It also enables application in biophotonics, and use in such applications as dense wavelength division multiplexers (DWDM), micro optical electro mechanical systems (MEOMS) and optical waveguide-based devices.

A wide variety of optical coatings can be patterned, including all dielectric multilayer reflectors, bandpass filters, dichroic edge filters, infrared blockers, or broad band antireflection coatings. In addition, enhanced metal reflectors, low reflectivity opaque metals, and electrically conductive transparent patterns can also be deposited by this technique.

The production of a patterned optical multilayer coated element begins with the preparation of the substrate by polishing and cleaning, and then application of a photoresist layer to the surface. Generation of a pattern is performed via mask alignment, photoresist exposure and development, creating a resist pattern on the surface to be coated. The prepared substrates are then placed into a vacuum chamber for deposition of the desired multilayer filter coating. Substrates may undergo exposure to a plasma source or a beam of energetic ions before coating deposition to better prepare the surface on an atomic scale, and during film deposition to enhance film quality and durability. Substrates also may be heated before or during coating deposition, in certain applications. Processes such as electron-beam evaporation, and ion-beam as well as magnetron sputtering can be used to create the multilayer filters. After deposition of the filter, the patterned coating is rinsed in a suitable solvent, removing the multilayer film and the resist from the unwanted areas, by means of a lift-off process. Finally, this sequence can be repeated as desired, allowing multiple filters to be deposited in arrays or other patterns. Additional details of the processes used to make these dichroic filter arrays have been well described elsewhere[9-11].

An example of such a patterned substrate with multiple wavelengths is shown below in Figure 2. The large horizontal lines are approximately 100 microns and narrow stripes are approximately 20 microns.

Figure 2. Three-wavelength band Patterned Dichroic Filter showing various spatial variations.

There are a number of advantages that can be realized with the use of this process to generate patterned optical multilayer coatings. Because the process relies on precision microlithography instead of cut metal masks to pattern the deposited coatings, features (coated areas) as small as 10 microns can be produced today, with spatial registration to adjacent coated areas within 1 micron. Work is underway to drive to features as small as 5 microns. Undesired "shadowing" or thickness drop-off of the coating at the pattern edges, unavoidable with cut masks, is eliminated due to the clean pattern edge break produced by the liftoff process. Intricate coating patterns of any shape or size can be manufactured without the limits imposed by practical machining limits of the metal masks. In addition, the cost of lithographic tooling does not increase greatly with pattern complexity, and has a longer usable life than cut metal masks placed on top of a substrate, which must be cleaned often to remove coating deposits, and can be easily damaged during loading, unloading, and storage.

The patterned dichroic filter coatings exhibit optical and physical properties similar to that of their traditional, non-patterned counterparts. The patterned films have a very high inherent resistance to environmental conditions such as humidity and temperature. Since the optical filter coatings are directly applied to the substrate/device, mechanical resistance to shock and vibration is improved over bonded discrete filter windows. This is a major advantage for these multispectral imaging applications.

In addition, as photonic technologies are miniaturized and integrated with microelectronic and micromechanical systems, the ability to selectively deposit multilayer optical structures directly onto the component enables the design engineer to include wavelength selective filtering structures early in the design process. It is no longer necessary to make a physical transition from micron sized on-chip structures to macroscopic diced and bonded optical filter elements and back again for wavelength selective integrated optoelectronic or optomechanical devices for imaging application.

One concern in this process is cleanliness and defect density. Using this methodology and refining it over time, we have produced hundreds of thousands of sharp-edged optical filter structures for a variety of applications, including spectral sensing and imaging, LCD and DLP displays, and entertainment lighting. We have recently enhanced our capabilities in this area by placing this entire process in a class 1000 clean room manufacturing space and adding magnetron sputtering to our plasma enhanced ion sputtering capability. Additional enhancements are also expected from new photolithography tools, including a semiconductor grade mask aligner that will help align the adjacent pixels with micron scale precision and repeatability.

3. PATTERNED PHOTODIODES

At the most basic level a photodiode is a type of photodetector capable of converting light into either current or voltage, depending upon the mode of operation. Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. When a photon of sufficient energy strikes the diode, it excites an electron, thereby creating a mobile electron and a positively charged electron hole. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. Materials commonly used to produce photodiodes include:

Table 1. Photodiode Detector materials and operating wavelength bands

Material	Wavelength range (nm)
Silicon	190–1100
Germanium	400–1700
Indium gallium arsenide	800–2600
Lead sulfide	<1000-3500

The material used to make a photodiode is critical to defining its properties, because only photons with sufficient energy to excite electrons across the material's bandgap will produce significant photocurrents. Due to their greater bandgap, silicon-based photodiodes generate less noise than germanium-based photodiodes. However if you want to detect any wavelengths greater than ~1 micron, germanium or InGaAs photodiodes must be used. This is an area for future investigations.

Complementary metal–oxide–semiconductor (CMOS) refers to both a particular style of digital circuitry design, and the family of processes used to implement that circuitry on integrated circuits (chips). CMOS circuitry dissipates less power when static, and is denser than other implementations having the same functionality. As this advantage has grown and become more important, CMOS processes and variants have come to dominate, so that the vast majority of modern integrated circuit manufacturing is on CMOS processes. CMOS technology is used to produce most of today's microprocessors, microcontrollers, static RAM, and other digital logic circuits. CMOS technology can also used for a wide variety of analog circuits such as image sensors in cell phone, data converters, and highly integrated transceivers for many types of communication.

The ability to utilize CMOS to make electrical devices and photodetectors on a single chip is enabling a major revolution in imagers and active pixel sensors. The single chip solution of a photodiode combined with the basic electrical function and ASICs to make a higher functioning device with active amplifier and integrated analog to digital converters will open up a plethora of new applications.

An active pixel sensor (APS), is an image sensor consisting of an integrated circuit containing an array of pixel sensors, each pixel containing a photodetector and an active amplifier. There are many types of active pixel sensors including the CMOS APS used most commonly in cell phone cameras and web cameras. Such an image sensor is produced by a CMOS process (and is hence also known as a CMOS sensor), and has emerged as an alternative to charge-coupled device (CCD) imager sensors. The term active pixel sensor is also used to refer to the individual pixel sensor itself, as opposed to the image sensor. In that case the image sensor is sometimes called an active pixel sensor imager, active-pixel image sensor, or active-pixel-sensor (APS) imager.

An example of a 2 x 8 array of active pixels with integrated analog circuits and an integrated Analog to Digital converter is shown below in Figure 3. The device (Taos TCS-3412) is configured as a color sensor for with four Red, Green, Blue and Clear color sensors as well as a broadband IR blocker deposited with the pattered dichroic filter technology discussed above. In addition each of the four color channel's electrical gain can be independently adjusted, balancing the spectral response due to the wavelength variation of the sensor's quantum efficiency. This device can be coated at the wafer level with thousands of sensors per wafer. The photolithography process has an added benefit in that the bond pad of the detector left uncoated.

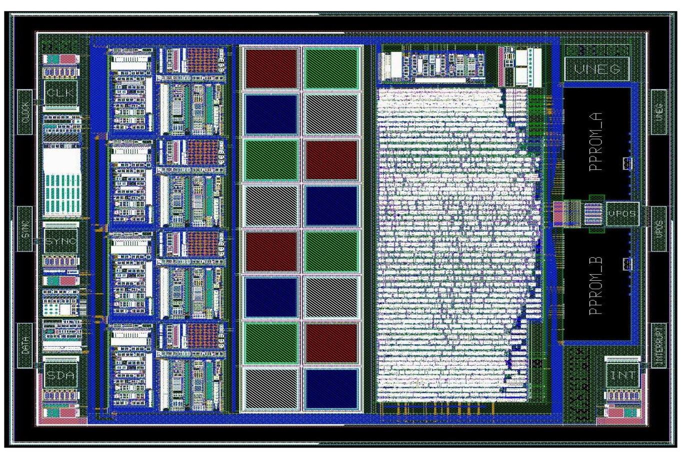


Figure 3. TAOS TCS-3414 Chip with integrated A/D, three color plus clear channels and integrated IR blocker.

Photodiodes and active pixel sensors are often used for accurate measurement of light intensity in science and industrial applications. They are also widely used in various medical applications, such as detectors for computed tomography (coupled with scintillators) or instruments to analyze biological samples (immunoassay). They are also used in blood gas monitors. All of these applications could be enhanced with these patterned sensors, where each individual pixel has a different wavelength passband.

4. MULTISPECTRAL IMAGERS

As discussed above, while some military or scientific studies may need hundreds of spectral channels, there are many more applications that require data over only a few well-defined wavelengths of interest. In our experience, this is a common syndrome: A researcher views his or her process at 100 distinct wavelengths, but in the end, only three to five wavelengths show anything of interest. These applications can all benefit from higher spatial resolution and significantly lower spectral resolution, which allows us to offer an economical alternative. Using our lithographically patterned dichroic filters, we can build multispectral imagers that capture a scene over a small number of spectral channels.

The coatings consist of multilayer stacks of high- and low-index materials fabricated via plasma-assisted deposition or magnetron sputtering. Adjusting the layer thickness and number of pairs tunes the spectral characteristics of the resultant coating to reflect or transmit over specific bands. As described above the lithographic process allows us to pattern an entire wafer in pixels as small as 10 µm on a side. The thickness of the filter directly limits how small the features can be. The thickness is defined by the filter design and the desired spectral properties of the filter. Features smaller than 10 µm have been fabricated utilizing different pattern geometries and for less demanding spectral filtering. Metallic lines smaller than 1 micron are also routinely deposited using the same techniques.

By alternating between deposition and lithographic patterning steps, we can form Bayer-filter-like structures corresponding to the wavelengths of interest for a specific application. We deposit the layers for the λ1 filter, lift off the patterning, re-pattern the wafer to apply the λ2 filter, and so on. In experiments, we have iterated through 11 successive depositions and patterns in a matter of a few days. The technology allows us to make a custom multispectral imager based on what the customer or application needs, with a direct pathway to high-volume production. A schematic of a 4-color, 6-color (including clear) and 8-color (including clear) dichroic filter array is shown below in Figure 4.

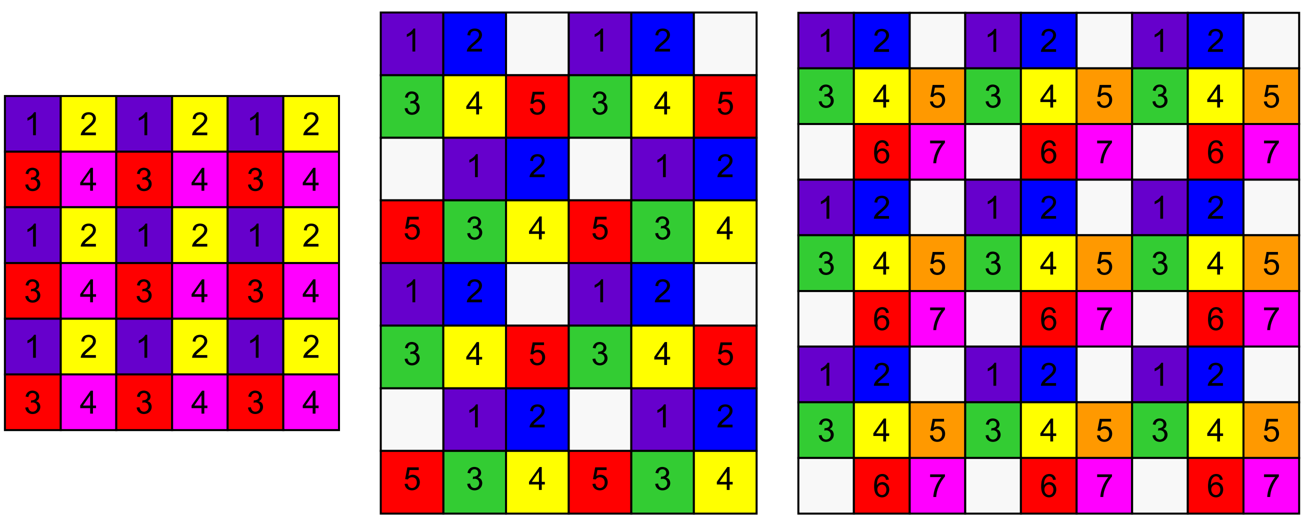


Figure 4. Examples of three different Bayer type dichroic filter arrays for multispectral imaging

We have complete control of the location of each filter limited only by the capabilities of the photolithography and our coating process.

One of the big challenges in traditional hyperspectral and multispectral imaging is how to extract useful information from the images. The computational burden imposed by the sheer size of the data cube can push the processing time to hours or days or more. That's fine for scientific research projects but few commercial applications can tolerate such delays. This is where the targeted wavelength approach offers significant benefits. A product developer working on a specific application typically already knows the absorption or emission characteristics of his materials of interest. The often have already performed hyperspectral analysis to determine the required wavelength bands. Once they have isolated their three to eight wavelength bands, we then tailor the dichroic filter to control the imaging wavelength bands for each pixel of the detector. One set of pixels can be completely transparent to provide a baseline reference value, for example. With this information, the software can mathematically compare the results of two or more other wavelengths to that reference wavelength.

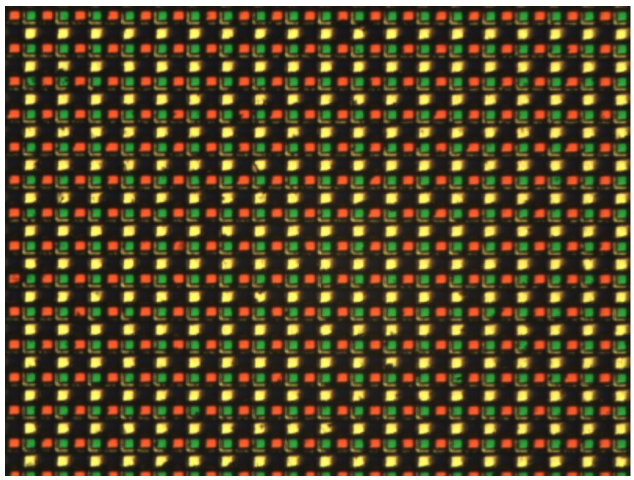
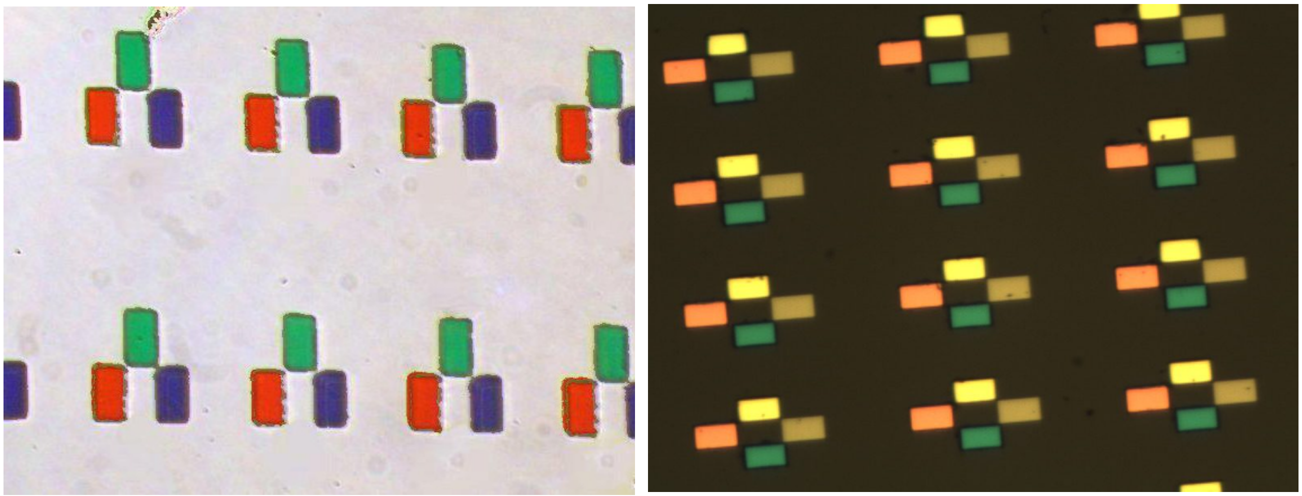


Figure 5. Three wavelength band square Patterned Dichroic Filters. Sharp-edged microscopic filter elements are routinely produced using our lithographic patterned coating process. The square filter elements are approximately 10μm in size.



(a) (b)

Figure 6 Microphotograph images of sparsely populated color filters. (a) is a filter designed to provide color images in low light level scenes and the (b) is designed to provide an additional IR filter. The rectangular elements are 19x33μm.

Figure 6a above is a pattern specifically designed to make a unique color camera that allows the addition of color with a very small impact on low light level performance and negligible impact on limiting resolution. The approach, which includes the NIR portion of the spectrum along with the visible is enabled by placing this filter directly on the surface of the surface of an EMCCD. It renders the correct hue in a real time, video rate image with negligible latency. Figure 6b shows the same pattern in reflection mode and has an additional filter for IR blocking[12].

Depending on the volumes needed for some applications the filters are coated on thin glass substrates and mounted directly onto the CCD or CMOS detector. For higher volumes the coating can be applied directly onto the wafer or standard wafer level packaging techniques. Utilizing wafer level packaging has an advantage that the patterned filter array coated glass wafer is merged and bonded to the silicon wafer before dicing. Some of the applications require a fixed spacer between the two wafers. We can utilize a black chrome netting between the layers for light beam shaping and to prevent spatial cross talk.

The custom Bayer filter approach involves very few tradeoffs. The image is captured in a single shot, so all wavelength data is acquired simultaneously. The method doesn't sacrifice much resolution just because you have a multispectral imager operating over 8 channels with an 8 megapixel detector. This is done in most off the shelf digital cameras sold today. They utilize advanced recursive algorithms to interpolate spatial content among different-wavelength pixels to form the images[13]. It requires some computation but it is a process performed by small FPGAs in nearly every digital camera, compared to the laborious task of sorting through gigabyte data cubes searching for features of interest.

A new custom Bayer-type filter can require non-recurring engineering charges for the design and build, but after that point the economies of scale offered by high-volume batch processing kick in. With the exception of the filters, our multispectral imager incorporates commercial off-the-shelf products, including detectors and optics. Once the customized filters are fabricated, they're placed atop detector arrays in a chip-level integration process. The approach is probably not practical for five systems unless the user needs simultaneous imaging and spectral content or a very small size. However, if someone wants to produce 500 or even 5,000 systems, dichroic filter arrays provide a pathway to get there at a fraction of the price of today's lowest cost multispectral or hyperspectral systems.

The dichroic filter array technology is also very scalable. Since we utilize photolithography to produce the arrays, it is just as easy to produce a 640 x 480 array as it is to produce an array for a 10 megapixel image sensor because the complexity lies not in the technique for implementing the camera itself but in the lithographically patterned dichroic filter. That simplicity is what makes the dichroic filter array based system very easy to build and easy to use.

5. APPLICATIONS

The key advantage of this new type of camera and imager is the ability to provide a compact system that is scalable to high volumes. These new imagers offer the unique advantage of scalability to tens of Megapixel resolutions, with compact size and no moving parts. Classic static operations like filter wheels on microscopes become dynamic, allowing the user to view the scene in multiple wavelengths simultaneously. Surface mapping of vegetation can be streamlined and units can be added to aircraft without regard to flight path or speed. New markets like 3-D imaging and 3-D animation, which to this point have used multiple CCD arrays, can now target end consumer use.

The applications go well beyond entertainment and security. In agriculture, vehicle-mounted systems can be used to monitor crops, detecting pests and diseases, assessing crop and soil nutrient levels, and helping forecast yield. Lower cost multispectral imagers can help ensure food safety by scanning produce for everything from fungi and dirt to bacteria, providing a means for preventing issues like the recent e-coli outbreaks in tomatoes, beef, and spinach or salmonella contamination in peanut butter. While there are hyperspectral systems for these applications, they are too bulky and complicated to be deployed to the supermarket, the field or the farm.

The technology has applications in environmental monitoring; for example, tracking pollutants from hazardous spills or monitoring smokestack output. In medicine, the devices could be used in fluorescence imaging spectroscopy to detect tumors in vivo or to monitor tissue oxygenation. The economies of scale of the coating process make it easy to field a scanner affordable enough to be placed in all surgical suites or even the bedside, on an average farmer's tractor, or at a packing house.

6. SUMMARY

The described patterned dichroic filter array approach takes a different path for multispectral imaging, from a science experiment to a commercial product. It is a lower-cost, higher-volume solution that is the perfect fit for a range of applications. It can't produce spectra at a thousand wavelengths but the target applications do not need that many wavelengths. In fact, most applications require between 3 and 6 wavelength bands plus a clear channel. In most cases the target customers have already performed hyperspectral imaging using traditional systems and they have already determined the wavelength bands they need. In addition, they really need an answer to if the all of tumor has been removed or if that leaf is contaminated, not a spectra. This technique, with the unique ability to tailor an image and a spectral response for a particular application, may open the doorway to a new class of valuable photonic solutions not addressable by today's current product offerings. They need a multispectral imaging product they can utilize at an affordable price, and lithographically patterned dichroic filter arrays provide the answer.

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