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# Pixel-Wise Multispectral Sensing System Using Nanostructured Filter Matrix for Biomedical Applications †

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**Abstract:** In this work, a novel multispectral sensing system consisting of nanostructured filter matrix and a charge-coupled device (CCD)-based image sensor has been developed to overcome the limitation of the conventional pigment filtered sensors, which are difficult to be fabricated at a microscale and usually showing a pronounced degradation. By designing the filters in guided-mode resonance (GMR) architecture, light transmission efficiencies of ~90% with low sidebands and sharp peaks can be obtained, which are critical characteristics for realizing precise optical measurement systems. To optimize the transmission functions, various materials and structural parameters have been simulated. Electron beam nanolithography is employed in the device fabrication to fabricate pixel-wise independent filter functions. After being characterized in terms of their wavelength filtering capability, the developed GMR filters are then combined with image sensors, particularly for addressing biological applications.

**Keywords:** nanostructure; multispectral sensing; color filter matrix; biomedical sensor

## 1. Introduction

Due to the world population explosion and rapid increase of healthcare costs, real-time health monitoring is more and more important and has drawn much attention in both scientific community and industry. To address this demand, light, which can be tailored as a very powerful tool can be used in biomedical applications [1]. Besides, after continuous exciting developments of light engines, efficient, robust, low voltage, and high brightness LEDs are now available to match the requirements in biomedical area, such as phototherapy, medical treatment, and optical sensing technology [2]. A large amount of optical system prototypes and commercial products have been developed in the past decades, aiming at providing non-invasive diagnosis and health monitoring.

However, up to now, most of the presently available sensors are too complex and expensive or measure only an insufficient number of health indicators. It is very desirable to have a sensor system capturing and measuring relevant health data quickly and reliably. To solve this, optical spectral analysis can be applied in sensing systems for measuring various body parameters and health indicators. One possible realization is to cover pixels of a CCD image sensor by specifically designed color filters, which can be controlled from pixel to pixel in terms of their filtering functions (Figure 1), to obtain a compact portable health monitoring spectrometer.

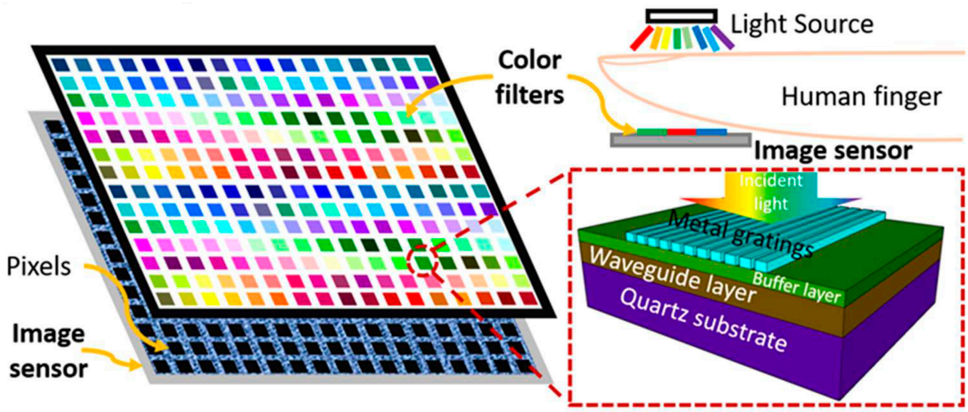


**Figure 1.** The schematics of the developed multispectral sensing system consisting of a broadband light source and an image sensor covered with color filter matrix (**top right**). Microscale filter matrix, which is based on a GMR filter architecture involving periodic gratings (**bottom right**), is set on top of image sensor (**left**).

## 2. Materials and Methods

Our measurement system works by shining a broadband light through our body part and simultaneously detecting the transmitted light with an image sensor covered by color filter matrix. Because molecules in the arterial blood have different optical absorption characteristics at different wavelengths, some body parameters can be deduced from the light intensity measured by altered pixels. To ensure its measurement accuracy, the transmission spectra of filter matrix should have low sidebands, high efficiencies, and narrow linewidths as system perquisites. Conventional filters made of pigments possess low transmission and purity and suffer from degradation [3], which usually leads to a large measurement uncertainty. Thus, nanopatterned filters are proposed in this work as an alternative solution to overcome the currently faced issues. These devices can be fabricated in a single-step nanolithography, in which their transmission properties can be controlled pixel-wise by adjusting the structural parameters [4].

GMR color filter based on a metallic resonant waveguide grating structure is experimentally demonstrated in this work, which is fabricated in microscale size in a single pattering step. The filter consists of both buffer and waveguide layers deposited on a quartz substrate, with silver gratings on top. The transmission properties are determined by its structural parameters (i.e., waveguide and buffer layer thicknesses, grating depth, periods, and filling factor).

## 3. Results and Discussion

To optimize the filter performance as well as to meet the filter requirements (i.e., high efficiency, narrow bandwidth, and low sidebands), all structural parameters including materials were carefully simulated using a commercial software tool of RSoft by Synopsys. Silicon nitride ($Si_3N_4$) was chosen as waveguide layer, while the buffer layer was made of silicon dioxide ($SiO_2$). According to our simulation results, silver is more suitable than other metals (e.g., aluminum) for gratings in the wavelength range from 600 nm to 1100 nm (i.e., optical window of human tissue). Afterwards, all structural parameters including the fill factor, thicknesses of waveguide and buffer layers, grating depth, and grating period were further analyzed. As a result, the optimum fill factor of 0.9 could be obtained. Thicknesses of waveguide, buffer, and adhesion layers (for silver grating attachment) are set to be 120 nm, 50 nm, and 4 nm, respectively. Meanwhile, the optimum silver grating depth is 50 nm. Using that optimum parameter set, the grating period was then varied from 350 nm to 710 nm, resulting in central filter wavelengths ranging from 600 nm to 1100 nm (Figure 2a).

When the pixels of the CCD sensor are small, the number of periods of the GMR sensor is also limited, potentially leading to crosstalk. Therefore, crosstalk between neighboring filter pixels with different distances *a* was also simulated (Figure 2b). From the simulation results, it is obvious that the main transmission peaks of neighboring filters with different distances are not shifted, although the transmission behavior around 800 nm slightly changes. As larger distance between filters can lead to a reduction of the transmission efficiency due to more metal coverage on the surfaces, its value will therefore be kept under 5 μm in the filter design.

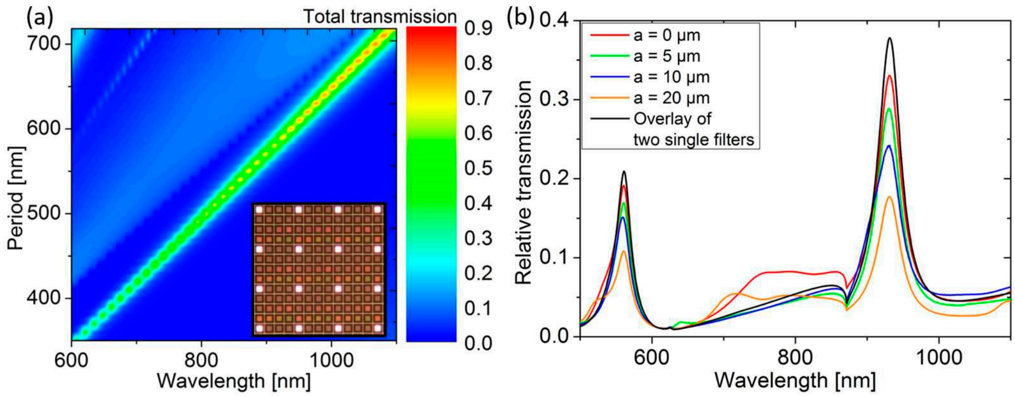


**Figure 2.** (**a**) Simulated transmission spectra of GMR filter with grating period ranging from 350 nm to 710 nm, covering the wavelength from 600 nm to 1100 nm. Inset shows fabricated filter matrix consisting of 15 individual filters and a hole cell without metal coating; (**b**) Simulated transmission spectra of two filters with distance of 0 μm, 5 μm, 10 μm, 20 μm and their single spectra overlay. These two filters have periods of 300 nm and 600 nm, respectively.

Afterwards the designed filter was fabricated and characterized, to compare with the simulation results. Firstly, the waveguide layer was deposited on a 400 μm quartz substrate by plasma enhanced chemical vapor deposition. Then, the buffer layer was conformally applied with atomic layer deposition technique. On top of the sample, the ITO adhesion layer was sputtered prior to metal deposition process. Subsequently, the silver gratings were patterned using electron beam lithography and lift-off process. A fabricated filter matrix is shown in Figure 2a. It comprises 15 individual filters with different grating periods and one bright cell without metal coating. Their transmission spectra were measured with a highly precise microscope and a fiber spectrometer. The measured transmission is around 13%, which is lower than simulated results. This phenomenon is mainly attributed to additional optical power loss at V-shaped metal gaps. Those undesired gaps can be avoided by reducing the proximity effect during e-beam lithography, which requires an optimized device fabrication flow.

At last, a TCD1208AP CCD sensor from Toshiba driven by a FPGA chip was used for data sampling in the developed integrated biomedical system (Figure 3). The finger of a test person will be illuminated by the light source on the bottom part (i.e., LED). The intensity of transmitted light is measured by the CCD sensor via the detecting window. The FPGA chip generates the necessary clocks for the sensor. Then, the measured data is converted via an amplifier stage with an A/D converter into digital signal, which will be stored in the RAM of the FPGA. The microcontroller reads the data and send them via UART-to-USB interface to computer, where the subsequent analysis step will follow. Using this setup, a heart rate of 71 beats per minute was obtained from a test person. Further measurements are necessary to investigate the capability of the developed sensor system.

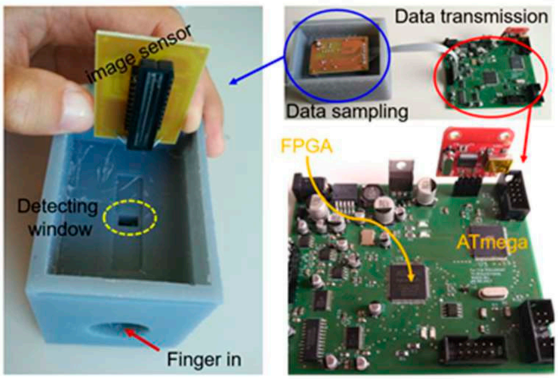


**Figure 3.** Integrated device comprising an LED, GMR color filter, and a CCD image sensor driven by a FPGA chip for biomedical inspection of human finger.

## 4. Conclusions

An opto-biomedical sensor system based on nano-structural color filter matrix and a CCD image sensor has been developed. Different structural parameters of the filters have been carefully studied by simulation, in which their optimum parameter set for sensor application is then determined. The transmission of fabricated color filters can cover visible and near infrared range when their grating periods are varied from 350 nm to 710 nm. For data sampling and transmission measurement, a CCD sensor driven by FPGA has been applied offering high portability. Such setup will be combined with fabricated filters for identifying more measurands of structural human health monitoring.

**Author Contributions:** W.W., J.D.P., H.S.W. and A.W. conceived and designed the simulations and experiments; W.W. and L.W. performed the simulations; W.W. and F.-N.S. designed and fabricated the measurement setup; W.W., P.H. and T.W. manufactured the color filter matrix; S.K. and B.B. designed and performed the transmission spectra measurements; W.W. analyzed the data; W.W. wrote the paper; H.S.W., B.B., S.K. and A.W. revised the paper.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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