Indium phosphide all air-gap Fabry-Pérot filters for near-infrared spectroscopic applications

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Abstract. Food quality can be characterized by noninvasive techniques such as spectroscopy in the Near Infrared wavelength range. For example, 930 −1450 nm wavelength range can be used to detect diseases and differentiate between meat samples. Miniaturization of such NIR spectrometers is useful for quick and mobile characterization of food samples. Spectrometers can be miniaturized, without compromising the spectral resolution, using Fabry-Pérot (FP) filters consisting of two highly reflecting mirrors with a central cavity in between. The most commonly used mirrors in the design of FP filters are Distributed Bragg Reflections (DBRs) consisting of alternating high and low refractive index material pairs, due to their high reflectivity compared to metal mirrors. However, DBRs have high reflectivity for a selected range of wavelengths known as the stopband of the DBR. This range is usually much smaller than the sensitivity range of the spectrometer detector. Therefore, a bandpass filter is usually required to restrict wavelengths outside the stopband of the FP DBRs. Such bandpass filters are difficult to design and implement. Alternatively, high index contrast materials must be can be used to broaden the stopband width of the FP DBRs. In this work, Indium phosphide all air-gap filters are proposed in conjunction with InGaAs based detectors. The designed filter has a wide stopband covering the entire InGaAs detector sensitivity range. The filter can be tuned in the 950−1450 nm with single mode operation. The designed filter can hence be used for non-invasive meat quality control.

1. Introduction

Near Infrared (NIR) Reflectance Spectroscopy in the ~930−1450 nm wavelength range, can be used for both, detection of diseases and noninvasive quality control, of food samples, such as meat, vegetables and wheat [1], [2], [3], [4], [5]. Miniaturized of such spectrometers will provide quick and mobile characterization of food samples. This can help health inspectors to detect the food quality on the spot rather than taking samples back to the laboratory, thus saving time and resources. Such miniaturized spectrometers can be built using Fabry-Pérot (FP) filters. Such filters consist of two highly reflecting mirrors with a central cavity between them, figure 1. The central cavity governs the output wavelength of the FP filter. Distributed Bragg Reflectors (DBRs) are the most commonly used mirrors in FP filters, due to their high reflectivity. DBRs consist of alternating layers of high and low refractive index materials. DBRs have high reflectivity for wavelengths around a central wavelength, which is governed by the optical thickness (refractive index × physical thickness) of the constituent layers, and is four times their optical thickness. DBR layers are therefore a quarter−wave thick of the center wavelength. The high reflection region of a DBR is known as the DBR stopband, and is governed by the refractive index contrast between the constituent layers. A broad stopband is desired, which can be achieved by a high index contrast between the DBR materials. Combining two DBRs to form a FP filter will result in a sharp transmission line inside the stopband of the DBRs. For FP filters with air-gap cavities, the transmission line is twice the cavity thickness. The transmission line can be tuned within the DBR stopbands by varying the cavity thickness. This can be achieved by electrostatic actuation of two electrodes placed at the two DBRs of the filter. An increased actuation voltage will result in an increased attractive force between the two DBRs. This will result in a reduced cavity and hence a shifted transmission line.

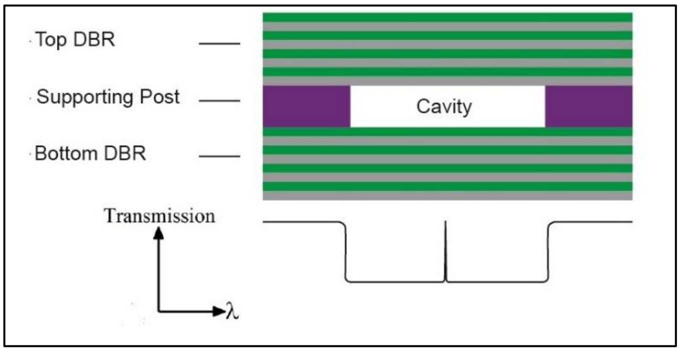

Figure 1. A FP filter with two DBRs and a cavity between them. A DBR consists of alternating pairs of high and low refractive index materials (shown in grey and green colors). Shown is also the transmission spectrum of the filter.

An exemplary NIR spectrometer is shown in figure 2. It consists of a NIR source, a FP filter and a detector.

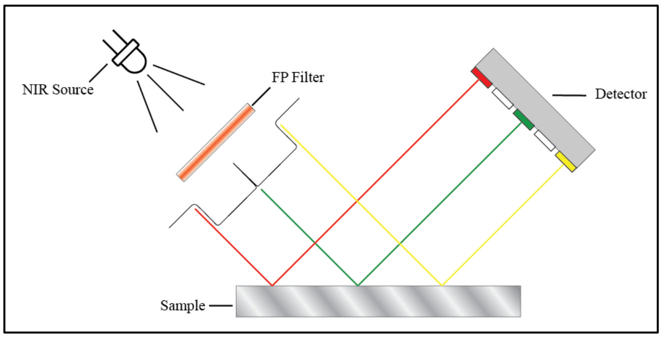

Figure 2. An exemplary NIR spectrometer. It consists of an NIR source, a FP filter and a detector. Wavelengths outside the stopband of the FP DBRs are also detected in this setup.

A detector usually has a much wider detection range compared to the stopband of the FP filter DBRs, figure 3. Indium gallium arsenide (InGaAs) based detectors provide the ideal detection range for the specified wavelength range. Indium phosphide (InP) and silicon dioxide (SiO_2) based DBRs provide a wide stopband at NIR wavelengths. However, the detection range of the InGaAs detector is still wider than the stopband of the FP filter DBRs, figure. 3. This will result in unwanted wavelengths reaching the detector, causing erroneous measurements. Therefore, the wavelengths outside the FP filter DBRs must be stopped from reaching the detector. However, InP all air-gap filters have a much wider DBR stopband. A carefully selected central wavelength could result in covering the whole range of the detector, therefore completely eliminating the need of any bandpass filter.

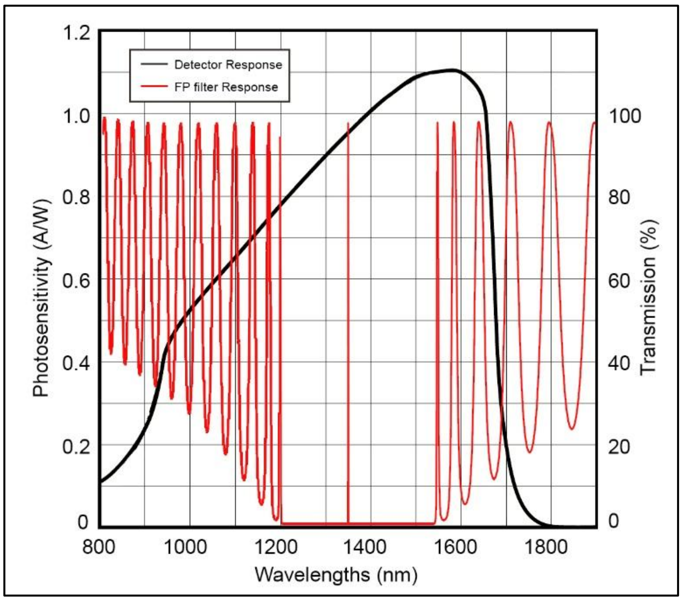

Figure 3. Photosensitivity of an InGaAs based detector (black) [6] and simulated transmission response of a FP filter (red) composed of InP and SiO_2. Wavelengths outside the stopband of the FP DBRs are also detected.

Although InP all air-gap filters have been developed for telecom applications [7], agri-food and environmental processing [8], no work has been reported for the above mentioned wavelength range (~930−1450 nm) to the best of our knowledge.

2. Design Requirements

As discussed earlier, the wavelengths of interest for classification and defect detection of meat samples are in the range ~930−1450 nm, while InGaAs based detectors are highly sensitive in the ~900−1700 nm range. Since, InP is highly absorbing below 950 nm, therefore only filters with passband above 950 nm are possible. Therefore, a FP filter with a stopband of 900−1700 nm is required which can be easily tuned in the 930−1450 nm range. The transmission line with in this range should ideally be more than 90%. Another requirement is that the filter must have single mode of operation for the entire tuning range (930−1450 nm). The line-width which is measured at half the maximum transmission should be as low as possible, ideally less as 2 nm.

3. Filter Design and Discussion

As discussed earlier, the central wavelength of the FP DBRs defines the stopband and the tuning range of the filter. Therefore, choosing the right central wavelength is essential to the filter design. An open source software *OpenFilters* is used to vary the central wavelength of the FP DBRs and to measure the output spectrum. The refractive index of InP in the wavelengths of interest used for the design of the filter is as in figure 4.

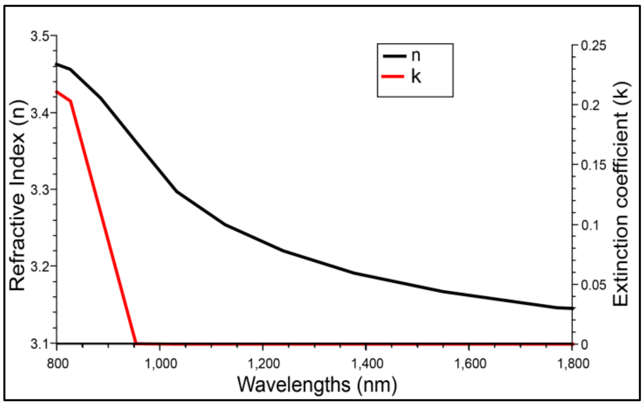

Figure 4. Refractive indexes n (black) and extinction coefficient k (red) of InP.

The advantage of using InP all air-gap filters is that they require only a few alternating layers to implement, due to the large refractive index contrast between the constituent layers. The filter with a DBR central wavelength of 1200 nm resulted in a stopband covering the whole range of the detector sensitivity, figure 5. The filter consists of only 5 InP/air-gap layers for each DBR, and therefore is easy to implement.

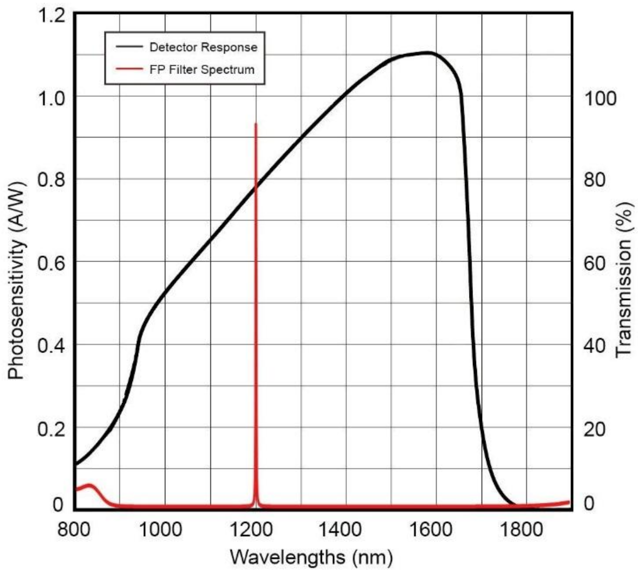

Figure 5. Photosensitivity of InGaAs based detector [6] and simulated transmission response of a FP filter (red) with a DBR central wavelength of 1200 nm. The stopband of the FP DBRs is wide enough to block the entire sensitivity range of the detector.

The InGaAs detector has very low sensitivity below 900 nm. Therefore, the small transmission of the filter below 900 nm can be ignored. For highly sensitive applications, a color filter (absorption filter) can be used as a substrate to eliminate those wavelengths. The filter is easily tuned between 950–1450 nm and beyond while maintaining single mode of operation, figure 6. The maximum and minimum transmission within in this range is 99% and 97% respectively. While the minimum and maximum line-widths within this range are 3.1 nm and 6 nm respectively. The minimum line-width occurs at a cavity thickness equal to the DBRs central wavelength, while the maximum line-width occurs at highest measured wavelength, i.e. 1450 nm.

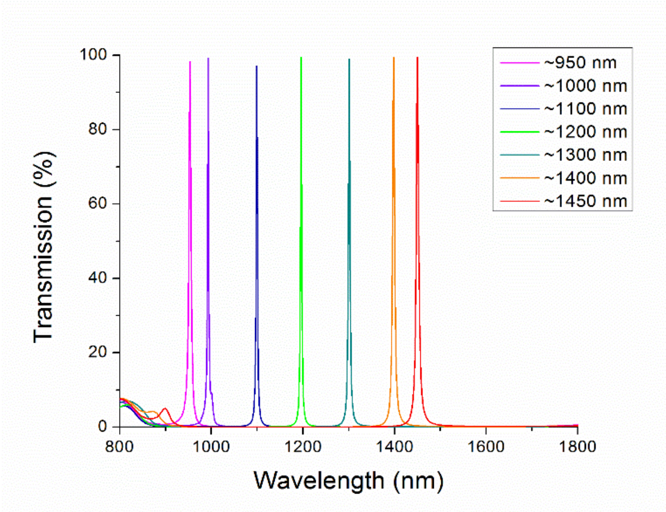

Figure 6. Transmission spectrum of an InP all air-gap FP filter (having DBR central wavelength of 1200 nm) with different cavity thicknesses.

4. Conclusions

In this work an InP all air-gap FP filter is presented to be used as an NIR spectrometer for food quality control. The filter has only 5 InP and air-gap layers for each DBR of the FP filter and hence can be implemented economically. The filter DBRs have a stopband covering the whole range of an InGaAs detector (~900–1700 nm), eliminating the need for an extra bandpass filter. The filter can be easily tuned in the 950–1450 nm wavelength range with more than 97% of transmission and a line-width not more than 6 nm. The best values of transmission and line-width, within the mentioned range, being 99% and 3.1nm respectively. The designed filter can easily be used for non-invasive quality control of food items, namely meat samples.

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