A Compact Tunable VCSEL and a Built-in Wavelength Meter for a Portable Optical Resonant Reflection Biosensor Reader

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This study reports a portable and precision photonic biosensor reader that can measure the concentration of a particular antigen using an optical resonant reflection biosensor (ORRB). To create a compact biosensor reader, a compact tunable vertical-cavity surface-emitting laser (VCSEL) and a compact built-in wavelength meter were manufactured. The wavelength stability and accuracy of the compact built-in wavelength meter were measured to be less than 0.02 nm and 0.06 nm, respectively. The tunable VCSEL emission wavelength was measured with the compact built-in wavelength meter, it has a fast sweep time (~ 10 seconds) and a wide tuning range (> 4 nm) that are sufficient for biosensor applications based on ORRB. The reflection spectrum of a plastic based ORRB chip was measured by the fabricated portable photonic biosensor reader using the VCSEL and wavelength meter. Although the reader is the size of a palmtop device, it could make a precise measurement of the peak wavelength on equal terms with a conventional bulky optical spectrometer.

Keywords : Optical resonant reflection biosensor, Tunable laser, Biosensor reader, Guided mode resonance filter

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I. INTRODUCTION

A photonic biosensor is very attractive to researchers because it uses light to detect the presence and low concentrations of biomolecules such as protein, glucose, and cells [1-3]. There are many types of photonic biosensors, including interferometer-based biosensors, waveguide-type biosensors, disk resonator biosensors [4], surface plasmon resonance biosensors [5], laser type biosensors [6], and grating-based biosensors. Recently, the grating-based biosensors

that use a guided mode resonance filter (GMRF) have become of great interest because they have the advantage of compactness and high-resolution sensing [7, 8]. In addition, a nano-imprint lithography technology for producing a GMRF on a plastic chip supports a low-cost biochip for mass production [9, 10].

Grating-based photonic biosensors operate by exploiting variations in the optical properties of the sensor. The concentration of the biomolecules can be determined by measuring the optical properties of the photonic biosensor,

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including the transmittance spectrum and reflectance spectrum. The optical properties of a grating-based photonic biosensor can be measured with a conventional spectroscopy system consisting of a broadband light source and an optical spectrometer. In this scheme, the measurement resolution is determined by the wavelength resolution of an optical spectrometer. However, a highly sensitive reader requires a high-resolution spectrometer with a large cavity. A high resolution spectrometer is not suitable for a portable instrument.

The optical properties of the grating-based photonic biosensors can also be measured using a scheme with a tunable laser instead of a large optical spectrometer. An optical component characterization system using a tunable laser is widely used in optical communication systems. This scheme uses a fine continuously tunable laser as a light source and has a very high-resolution. There are many types of tunable lasers such as an external cavity tunable laser diode (LD) [11], sampled grating distributed Bragg reflector tunable LD, thermal tunable VCSEL, and frequency swept laser using a wavelength scanning filter [12]. Tunable lasers are also used in gas detection systems [13]. Although commercial optical component characterization systems using a tunable laser are available, they are not suitable for portable devices.

A photonic biosensor reader is an instrument that can measure the reflectance spectrum of a biosensor. To use a photonic biosensor in a personal health monitoring system, a portable biosensor reader is mandatory. A photonic biosensor reader using a high-resolution spectrometer is not suitable for portable instruments nor is a photonic biosensor reader using commercial instrument grade tunable laser system. A photonic biosensor reader with a compact tunable laser diode and a compact built-in wavelength meter is compact. It represents a viable solution for the realization of a portable biosensor reader that could screen/diagnose acute myocardial infarction by measuring cardiac marker concentrations such as cardiac troponin I (cTnI) and creatine kinase MB (CK-MB) for application to a personal health monitoring system. The biosensor reader introduced in this paper has a more compact structure and a much higher measuring resolution than a conventional spectrometer system.

II. A PHOTONIC BIOSENSOR AND MODULES

The photonic biosensor introduced in this paper is a grating based photonic biosensor which contains a GMRF. A GMRF is a diffraction grating with a subwavelength period structure made of high refractive index material. Fig. 1 shows the structure of the GMRF.

A GMRF consists of a substrate, a subwavelength period grating made of polymer resin, and a high refractive index coating on a subwavelength grating [8]. The substrate is made of glass or plastic. The refractive index of the glass is about 1.47. The subwavelength grating was made of

FIG. 1. Structure of the guided mode resonance filter.

polymer resin and fabricated using a nano-imprint technique. The typical value of the refractive index of the polymer resin is about 1.55. High refractive index material such as SiN_x or TiO_2 is coated on the subwavelength grating. The typical value of the refractive index of SiN_x is 2.00. The refractive index of the target materials is smaller than that of the high refractive index coating. The reflection spectrum of the GMRF can be found by using rigorous coupled-wave theory [8, 14].

The target material is a layer of biomolecules. To use a MRF as a biosensor, an antibody of a specific antigen such as cTnI or CK-MB is immobilized on the grating of a GMRF as a target material. This structure is termed an optical resonant reflection biosensor (ORRB). The structure of the ORRB was carefully designed to have a sharp resonance peak in the reflectance spectrum.

Fig. 2 shows the principles of an ORRB. Fig. 2 (a) depicts a schematic diagram of an antibody-antigen interaction on the surface of a GMRF. A Y-shaped antibody immobilized on the surface of an ORRB captures an antigen. Effective index of a guided mode in a GMRF is changed by the interaction, and the peak wavelength is shifted. The dotted line in Fig. 2 (b) shows the reflection spectrum of an ORRB before an antigen-antibody interaction. Y-shaped antibodies are immobilized on the surface of the ORRB, and the antigen-antibody interaction has yet to occur. The reflectance spectrum of the ORRB before the antigen-antibody interaction shows a sharp resonance peak. After the antigen-antibody interaction, the optical thickness of the top layer of the ORRB changes. The solid line in Fig. 2 (b) shows the reflection spectrum after the antigen-antibody interaction. The reflection spectrum of the ORRB after the antigen-antibody interaction also shows a sharp resonance peak. However, the resonance peak wavelength after the antigen-antibody interaction shifts. By measuring the resonance peak shift ($\Delta\lambda$), the existence of a specific antigen can be determined, and the concentration of any antigens existing in the sample can be measured. Typically, the amount of the peak wavelength red-shift caused by the antigen-antibody interaction is 0.1~1.0 nm for immunoglobulin (IgG), cTnI, CK-MB, myoglobin [15, 16].

Fig. 3 shows an image of the ORRB chip. The size of the ORRB chip is 39.4 mm by 19.9 mm. Five ORRBs exist on the ORRB chip. The GMRF of an ORRB is fabricated using a nano-imprint technique. This ORRB chip is suitable for mass production. It is possible to immobilize

FIG. 2. Measuring principle of an ORRB: (a) Schematic diagram of an antigen-antibody interaction and (b) Reflectance spectra from an ORRB before (dotted line) and after (solid line) an antigen-antibody interaction.

FIG. 3. An image of an ORRB chip. (a) Five ORRBs were fabricated on the ORRB chip. (b) Orientation of the grating. When measuring the reflectance of the ORRB, a linearly polarized light must be used. The arrow line shows the direction of the polarization.

different antibodies on each ORRB of the ORRB chip. In this case, multiple antigens can be detected simultaneously using a single ORRB chip. ORRBs are carefully designed to have a sharp resonance reflectance peak and a peak wavelength of approximately 787 nm.

To detect antigens using an ORRB, the reflectance spectra of the ORRB must be determined. A photonic bio-

FIG. 4. Schematic of the portable photonic biosensor reader.

sensor reader measures the reflectance spectrum of an ORRB before and after the antigen-antibody interaction and calculates the wavelength shift $\Delta\lambda$. From $\Delta\lambda$, it determines the existence of a particular antigen and its concentration, if it exists, in the sample.

Fig. 4 shows the schematics of the portable biosensor reader. The biosensor reader measures the reflectance spectrum of an ORRB chip shown in Fig. 3 using a tunable VCSEL. As shown in Fig. 4, the biosensor reader system consists of a compact tunable VCSEL, a compact wavelength meter, a data acquisition system (DAQ), and a WinCE board. The WinCE board controls the entire operation of the photonic biosensor reader. It controls the DAQ via the RS232C protocol. It also controls the LCD display panel. The DAQ system controls the photodiodes and the tunable VCSEL.

The light from the tunable VCSEL propagates to the first beam splitter (BS). The first BS splits the light into two directions. The beam that passes the first BS propagates to the linear polarizer. As an ORRB has strong polarization dependency, a linear polarizer is used to fix the polarization of the incident beam on the ORRB in this case. TM polarization, where the electric wave is perpendicular to the grating lines, was used because TM polarization has sharper peak characteristics than TE-polarized light. After the linear polarizer, the beam propagates to the second BS. The optical power of the beam which passes the second BS (P_{VCSEL}) is measured using a photodiode (PD_1). If the second BS is a 50:50 BS, P_{VCSEL} is equal to the optical power of the incident light on the ORRB. The beam reflected by the second BS is directed to the ORRB and reflected. The optical power of the reflected light from the ORRB (P_{REFL}) is measured using another photodiode (PD_2). If the second BS is a 50:50 BS, P_{REFL} is half of the optical power of the light reflected by the ORRB. The reflectance of the ORRB at the VCSEL output wavelength

is $2P_{\text{REFL}}/P_{\text{VCSEL}}$. Since an absolute value of the reflectance is not important, $P_{\text{REFL}}/P_{\text{VCSEL}}$ is taken as a reflectance. The absolute value of the reflectance can be measured after calibrating the biosensor reader using a reflectance standard. A reflection spectrum is obtained by taking reflectance while sweeping the output wavelength of the VCSEL.

The beam that is reflected by the first BS propagates to the compact wavelength meter module. The reflection spectrum is not accurate without a wavelength meter. To measure the wavelength of the VCSEL accurately in real time, a wavelength meter that uses a ratiometric wavelength measurement scheme was manufactured [17].

One of the key components of the photonic biosensor reader is its tunable VCSEL. A tunable VCSEL is used as the tunable light source. Here, a tunable VCSEL was fabricated for the biophotonic sensor reader. The tunable VCSEL has an internal device heater structure [18]. In this structure, another VCSEL (heater) is fabricated next to the light-emitting VCSEL. If current is applied to the heater, the heater generates heat. This heat tunes the output wavelength of the VCSEL. Light output from the heater is blocked. Fig. 5 shows an image of the tunable VCSEL (a) and the output spectra (b). The tunable VCSEL was packaged with TO-CAN. It has a diameter of 7.6 mm and a height of 5.2 mm. The VCSEL chips were mounted on a submount with a thermoelectric cooler (TEC) and a thermistor. The TEC serves to cool and control the tem-

FIG. 5. Compact Tunable VCSEL: (a) photo image, and (b) output spectra as a function of the heater current.

perature of the VCSEL chip actively to facilitate fast sweeps of the wavelength. Fig. 5 (b) shows the output spectra of the packed tunable VCSEL as a function of the heater current. The tuning range of the tunable VCSEL is greater than 5 nm. The emission wavelength is 787 nm at room temperature, and the linewidth is as narrow as 0.2 nm. A detailed explanation of the tunable VCSEL structure can be found in the literature [18].

The other key component of the photonic biosensor reader is its compact wavelength meter. The output wavelength of the VCSEL is controlled using heater current. As it is not possible to control the output wavelength of the VCSEL precisely using a heater current, it becomes necessary to measure the output wavelength of the tunable VCSEL. The resonance peak wavelength is not accurate without the use of the wavelength meter. Some instrument grade tunable lasers provide wavelength voltage output. A periodic wavelength standard is used in some tunable laser optical component characterization system and it is not suitable for a portable instrument.

To monitor the output wavelength of the tunable VCSEL in real time, a wavelength meter that utilizes a ratiometric wavelength measurement scheme was manufactured [19]. Fig. 6 shows a schematic diagram (a) and a photo image (b) of the manufactured wavelength meter. An edge filter

FIG. 6. (a) Schematic of the compact wavelength meter, and (b) image of the compact wavelength meter module (left side) including an edge filter (right side).

was designed and fabricated to ensure that it has wavelength-dependent transmittance and reflectance. The edge filter is a 4 mm cube consisting of two triangular prisms as shown on the right side of Fig. 6 (b), and a dielectric material is coated on the surface of one of the two prisms to ensure wavelength-dependant transmittance.

The dielectric coating parameters were designed to cover the tunable VCSEL wavelength tuning range. The transmittance of the fabricated edge filter increases monotonically from 780 nm to 795 nm. Due to the polarization dependency of the edge filter, a linear polarizer is positioned before the edge filter. The incident light on the edge filter is therefore linearly polarized. Another photodiode (PD₃) is used to measure the optical power (P_{TR}) of the transmitted linear polarized beam that passes the edge filter. A fourth photodiode (PD₄) is used to measure the optical power (P_{REF}) of the beam that is reflected by the edge filter. There is a one-to-one correspondence between P_{TR} / P_{REF} and the wavelength of the incident light on the edge filter. As the output of the VCSEL is monochromatic, the emission wavelength of the tunable VCSEL can be determined by measuring the P_{TR} / P_{REF} ratio of the edge filter. The manufactured wavelength meter module is very compact, as depicted on the left side of Fig. 6 (b); thus, it is suitable for use in a portable instrument.

The wavelength meter must be calibrated to measure the tunable VCSEL output wavelength from the ratio of P_{TR} / P_{REF} . The ratio values of P_{TR} / P_{REF} are measured and, as shown in Fig. 4, the output wavelength of the tunable VCSEL is measured by an optical spectrum analyzer simultaneously for various output wavelengths. Fig. 7 shows the characteristics of the wavelength meter. Fig. 7 (a) illustrates the relationship between the P_{TR} / P_{REF} ratio and the output wavelength of the tunable VCSEL. The relation curve was obtained by fitting the data of a fourth-order polynomial for a range of $0.759 \leq P_{TR} / P_{REF} \leq 1.95$. The dotted line is the obtained fitting curve, and the maximum fitting error is 0.042 nm. In the ratiometric wavelength measurement scheme, the wavelength measurement rate is limited exclusively by the sampling rate of the electronics, which, for our reader, is fast enough to monitor the laser wavelength in real time. Though a particular edge filter was created in this study, an edge filter for special wavelengths is also available. A linear transmittance filter is a special type of edge filter whose transmittance varies linearly over a given wavelength range. It is particularly suitable for wavelength measurements. A commercial product that incorporates a linear transmittance filter for the C band (1530 to 1565 nm) is available.

To test of characteristics of the wavelength meter for a biosensor application, the accuracy and stability were also measured because these characteristics would be slightly varied by environmental changes in factors such as the laser power and the polarization status. Fig. 7 (b) depicts wavelength errors for the measured wavelengths. The wavelength errors were obtained from the difference between

wavelengths measured by a calibrated optical spectrum analyzer and the wavelength meter. The wavelength error was within 0.06 nm. Fig. 7 (c) illustrates the wavelength variation during ~ 4 minutes measured by the wavelength meter. The stability of the measured wavelength was less than 0.02 nm for few minutes. Because ORRBs measured biomarker concentrations by detecting the peak wavelength shift, the stability/resolution is the most important parameter.

Because the peak wavelength shift of a general GMRF by antigen-antibody interaction is 0.1~1.0 nm for biomarker

FIG. 7. The characteristics of the constructed wavelength meter. (a) VCSEL emission wavelength as a function of P_{TR}/P_{REF} . The fitted results are shown as a dotted line, (b) the difference between two wavelengths measured by the wavelength meter and a calibrated optical spectrum analyzer, and (c) the stability of the measured wavelength by the wavelength meter.

concentrations of 1 pg/ml ~ 1 ug/ml [15, 16], a wavelength meter with high stability (<0.02 nm) will be used for biosensor applications.

III. ORRB READER

In a biosensor application, a grating-based biosensor reader measures the molecular concentration by detecting the resonance peak wavelength shift of the grating reflection spectrum. As the biomolecular layer on the photonic biosensor thickens, the peak wavelength shift changes with time [8]. If the wavelength sweeping speed of the tunable VCSEL is not fast, the peak wavelength shifts during the measurement. A fast VCSEL tuning speed is therefore an important feature for biosensor applications. However, it is difficult to test a fast-tuned tunable VCSEL because the sweeping speed of an optical spectroscopy or optical spectrometer is too slow.

To test the wavelength sweeping speed and wavelength tuning range of the tunable VCSEL proposed here, the wavelength of the tunable VCSEL was tuned by providing a heating current to the internal heater and then the wavelength with the manufactured wavelength meter positioned in the biosensor reader was measured. Fig. 8 shows the tuning test results. The dotted line in Fig. 8 (a) is the temperature measured by the thermistor installed inside the VCSEL package. The tuning of the VCSEL is done in three steps: in Step A the heater is turned on and the wavelength is increased by the internal heater; in Step B natural cooling occurs and the heater is turned off; in Step C forced cooling puts the laser in standby mode.

Step A is the tuning step. The VCSEL is turned on at the beginning of Step A. The current applied to the internal heater is increased from 0 mA to 70 mA in 10 s. The output wavelength is then increased monotonically with time. The wavelength tuning range is 3.4 nm and the average wavelength sweep rate is 0.34 nm/s. This tuning speed is sufficient for a typical biosensor application. In the thermistor, the temperature rises from 5°C to 40°C.

Step B is a natural cooling step. Although the heater current is turned off at the beginning of this step, the wavelength increases continuously for 3 s due to the presence of residual heat. The wavelength rapidly decreases by 2 nm and then slowly decreases near room temperature. At the end of Step B, the cooling speed is very slow and the tunable VCSEL is turned off.

Step C is the standby step. For a sufficient wavelength tuning range, the starting temperature of the VCSEL tuning must be lower than room temperature. The TEC is turned on at the beginning of Step C and cools the VCSEL. The temperature drops from 29.5°C (room temperature) to 5°C in 2 s. After the target temperature is reached, the TEC maintains the temperature until the next wavelength tuning.

All steps were performed within 50 s in this test, and

FIG. 8. (a) VCSEL emission wavelength and temperature as a function of time, and (b) sweep frequency test of the tunable VCSEL.

the tuning range was 3.4 nm. The intervals of the sweeps can be shortened. The full wavelength sweeping time is shorter than 10 s, which may be fast enough to observe the response to the interaction between the antibodies and the biomolecules.

Only one wavelength sweep is sufficient to test the optical properties of the common optical components. In the biosensor application, the spectral shift of the sensor's optical properties, such as transmittance or reflectance is measured [15, 21]. The optical properties of the sample must be measured several times. After each wavelength sweep is completed, the emission wavelength of the VCSEL rapidly returns to its initial wavelength. For thermal tuning of the VCSEL, the cooling speed may be very slow if there is no cooling component, such as a TEC.

To test this performance, the tunable VCSEL was tuned six times. Fig. 8 (b) shows the results. After each forced cooling step, the tunable VCSEL rapidly returns to its initial state. This behavior shows that the VCSEL can be used to monitor time-varying optical properties, which are an essential feature of biosensor applications.

The manufactured portable biosensor reader is depicted in Fig. 9 (a). The photonic biosensor reader is 150 mm wide, 120 mm deep and 46 mm high. Fig. 9 (b) shows the reflectance spectrum of the ORRB without biomolecules

(a)

(b)

FIG. 9. (a) An image of the portable biosensor reader, and (b) results of the reflectance measurement of an ORRB sample without anti-bodies fixed on the GMRF.

using the portable reader. Given that the peak wavelength of the reflectance spectrum is measured, the absolute value of the reflectance is not important. Consequently, there is consequently no need to calibrate the reflectance value or measure the relative value. After the measurements are taken, the wavelength is calculated by using a fitting equation. The peak wavelength of the reflectance spectrum is 789.4 nm. The reflectance spectrum shows a small ripple with a period of approximately 0.33 nm. The ripple is presumed to come from interference at the optical components of the reader.

IV. CONCLUSION

A portable grating-based precision biosensor reader was formulated in this study. The constructed photonic biosensor reader was demonstrated to be sufficiently portable. It is 150 mm wide, 120 mm deep and 46 mm high. To enhance the compactness of the reader, the key components of a compact tunable VCSEL, a compact wavelength meter module, and a GMRF on a biosensor chip were fabricated. The internal wavelength meter with a compact edge filter

is calibrated by an external optical spectrum analyzer. It has a stability of <0.02 nm during few minutes and can measure the VCSEL emission wavelength in real time. The fabricated tunable VCSEL has an internal heater, a TEC, and a thermistor for the control of the temperature. The wavelength tuning test of the VCSEL was accomplished by using the constructed wavelength meter, and the test results confirmed that the tuning speed and tuning range are both sufficient for biosensor applications. The portable reader was successfully used to obtain the reflectance spectrum of the fabricated ORRB. The spectrum showed a clear peak.

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