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To cite this article: F D Laksono et al 2018 J. Phys.: Conf. Ser. 1011 012043

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Development of low cost and accurate homemade sensor system based on Surface Plasmon Resonance (SPR)

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Abstract. In this paper, we developed homemade and computerized sensor system based on Surface Plasmon Resonance (SPR). The developed systems consist of mechanical system instrument, laser power sensor, and user interface. The mechanical system development that uses anti-backlash gear design was successfully able to enhance the angular resolution angle of incidence laser up to 0.01°. In this system, the laser detector acquisition system and stepper motor controller utilizing Arduino Uno which is easy to program, flexible, and low cost, was used. Furthermore, we employed LabView’s user interface as the virtual instrument for facilitating the sample measurement and for transforming the data recording directly into the digital form. The test results using gold-deposited half-cylinder prism showed the Total Internal Reflection (TIR) angle of 41.34°± 0.01° and SPR angle of 44.20°± 0.01°, respectively. The result demonstrated that the developed system managed to reduce the measurement duration and data recording errors caused by human error. Also, the test results also concluded that the system’s measurement is repeatable and accurate.

1. Introduction
Surf cple Plasmon Resonance (SPR) can be described as a collective resonance on the oscillations of electrons in the valence band in a material by light [1]. The light coming through the medium boundary with the angle comes greater than the critical angle when it concerns the boundary surface resulting in the total internal reflection (TIR) optical phenomenon. When the TIR occurs, the refractive electromagnetic waves have a field waveform with amplitude decaying exponentially away from the boundary plane of two mediums called evanescent waves. The resonance condition is achieved if the frequency of the light photon corresponds to the natural frequency of the electrons of the surface oscillating against the atomic restoring force. When the resonance takes place on a planar surface, there is a surface plasmon (SP) excitation which is a surface electromagnetic wave with the direction of propagation parallel to the metal / dielectric boundary plane[2].

When the SP wave vector and the evanescent wave vector corresponding to the magnitude, then the resonance is eliminated due to the phase difference. As a result, at a certain angle of light occurs attenuated total reflection (ATR) is marked by a drastic reduction in the intensity of reflected light [3]. Wave oscillations in the boundary plane of the metal and the outer medium are very sensitive to any changes in this boundary, for example, the change due to absorption by molecules on the metal surface. If the change occurs then the ATR angle shifts. The magnitude of the ATR angle and its shift is a parameter of the magnitude measured by the SPR instrument [4].

The commercial instrument has several advantages such as easy to operate and precise measurement results. On the other hand, however, commercial instruments are usually treated as a black box and
only produce results without knowing the actual process [5]. As for the SPR homemade instrument has many advantages, including researchers, have full access to the operation of the system, and it is possible to modify the configuration according to the research scheme[6,7]. SPR homemade is also cheaper and can be modified both hardware and software.

The SPR instrument mechanical system enhanced by anti-backlash gear based on the Torsional Spring-Loaded Anti-backlash model [8–11]. The laser detector acquisition system and stepper motor controller utilizing Arduino Uno which is easy to program, flexible, and low cost, was used [12]. LabVIEW’s user interfaces as the virtual instrument for facilitating the sample measurement and for transforming the data recording directly into the digital form. Also, LabVIEW is simplified application development and have been customized for data acquisition systems, software simulations, embedded electronics, and real-time controls [13].

2. Instrument Design

The basic design of homemade and computerized sensor system based on SPR is shown in Figure 2. The main component is a Mechanical system, optic system, and computerized system. The optic system includes a low power laser (HeNe 632.8 nm, 3 mW), two detectors (one and two), a polarizer, a beam splitter. The computerized system consists Main Unit and Computer. The half-cylinder prism was deposited by gold and mounted on prism holder.

![Figure 1. Ideal SPR spectra.](image1)

![Figure 2. block diagram of the SPR instrument.](image2)

![Figure 3. Real SPR instrument set-up in this paper.](image3)

Angle scanning to find SPR angle is performed by measuring reflected light intensity as the prism and detector rotated in the θ-2θ mechanism. Prism and detector are rotated by angle θ and 2θ respectively. The data plotted on the SPR graph is shown in Figure 1 are angles and reflections. The experimental SPR spectra measurement of the gold thin film shown in Figure 2. The light from LASER pass through a polarizer to enhance the overall SPR signal by removing the light from a laser that's not polarized in TM mode or parallel to the plane of incidence. The P polarized laser beam then divided into two parts with the same wavelength and intensity by the beam splitter. One part of the laser beam to the first laser detector as the reference laser intensity. The other part of the light is reflected by the prism toward the second laser detector as the laser intensity. Reflection data obtained by dividing intensity from detector two (2) with detector one (1). Real SPR instrument set-up is shown in Figure 3.

2.1 Mechanical system

The mechanical system shown in Figure 5, includes two motor stepper, two torsional spring-loaded anti-backlash gear, detector holder, and prism holder. The hybrid stepper motor is used to obtain good torque and angular, which the angular resolution is 1.8°/step. Wheel gear that connected to the worm gear is designed with 180 teeth to obtain 1:180 ratio. Both motor steppers utilize a worm drive that
rotates the table 1° for 100 full steps of the stepping motor. This defines the accuracy of the instrument which is ±0.01° for both the resonance and critical angle.

The repeatability measurement of SPR spectra enhances by a torsional spring-loaded anti-backlash gear as wheel gear. The anti-backlash gear used to reduce backlash of the mechanical system. Design of torsional spring-loaded anti-backlash gear shown in Figure 6. Anti-backlash gear has two wheel gear which connected by spring. Mechanism of anti-backlash gear has two wheel gear with backlash shown in Figure 4. In Figure 4 (a) wheel gear g1 and wheel gear g2 interact, but having a space between the interconnected teeth causes a backlash. In Figure 4 (b) the anti-backlash gear g1 has two-wheeled gears whose direction of emphasis differs due to the spring effect. Therefore, when wheel gear g1 interacting with the wheel gear g2 there is no space then minimize the backlash. The torsional spring-loaded anti-backlash model has a very good accuracy level on small loads.

![Figure 4](image1.png)

**Figure 4.** (a) Wheel gear with backlash and (b) anti-backlash gear

![Figure 5](image2.png)

**Figure 5.** Mechanical system in this paper

![Figure 6](image3.png)

**Figure 6.** Design of torsional spring-loaded anti-backlash gear

3. Electronic System

The electronic system has three tasks. First, to drive two motor stepper, each one with a bipolar stepper motor. Second, to convert the analogical response of the photodiode to a digital value. Third, to respond any command and send data to the computer. These three tasks executed through USB commands as a serial signal.

The electronics of the main unit of the SPR instruments consists of a microcontroller based system (Arduino UNO), which was selected because it has USB connectivity, cheap, and facilitates the control of the system by synchronizing with LabView Software. This electronic system is composed of a microcontroller, a power supply, motor driver, and a computer. There is two analog input; these are the main photodetector and the reference photodetector. Also, the microcontroller gives us threaten digital output to control the stepping motors via motor drivers.

The photodetector used is Si photodiode (OPT101, Texas Instrument). This photodiode selected because has fast responses, built in with trans-impedance amplifier, high linearity light power, and voltage. The photodetector directly connected to ADC device (ADS1115) to reduce possible noise causes of long analog cable. Besides, this ADC device has 16bit resolution and I2C communication protocol which support with Arduino UNO. When ADS1115 gain amplifier set to ±4.096V, then the resolution is 125µV. The light reflected or transmitted by SPR instrument detect by photodetector converted to a voltage. This voltage converted to digital form and sent to Arduino UNO by ADS1115.

In the movement routing, the photodetector motor rotated two steps (0.02°), and the sample motor rotated one step (0.01°), then the ADC is started to sample the sensors. The main value measured by SPR instrument corresponds to the angle when the minimal intensity of the light occurs. This angle determined from the measured angle dependence on the reflected light of the voltage form, where
voltage proportional to incident light. Software counters are used to know the actual position and determine when the system has to stop. This software uploaded inside the microcontroller Arduino UNO. The Arduino UNO labeling each data to aid LabVIEW software to organize all data collected.

4. LabVIEW Software Interface
The LabVIEW software to be the interface between SPR instrument and user. The state machine diagram is shown in Figure 7 and the block diagram shown in Figure 8. Each program made in LabVIEW is called a virtual instrument and construct of three component. A front panel which is the user interacts a block diagram which is the program that controls the front panel and icon/connector which is connecting between programs (represent with the box in Figure 8).

![Figure 7. State machine diagram of user interface](image)

![Figure 8. Partial source code of LabVIEW program](image)

![Figure 9. The front panel of the LabVIEW program is showing the user interface of the "SPR angle scanning" tab.](image)

![Figure 10. Comparison of resonance angle measurement of half-cylinder prism for the manual system developed a system (Automated), and theory-based simulation.](image)

The program begins with the circle in the top left corner, then initialize all electronic and program component. "loop" cycle (above wait for event diagram) serves to make selection state (action) in the user menu. The Software interface consists of one pop-up window and five tabs. The following describes the function of each tab.

- **Setting port.** This Pop-up window shows a box to determine the serial port used for communication between LabVIEW and SPR instrument. The communication port uses a serial signal passed over USB so that the port name is prefixed by COM. The port number used is the serial port connected to the Arduino UNO microcontroller.

- **SPR angle scanning.** The signal of the light received by detector one and detector two is graphed in real time. In this tab, the initial and final degrees should be specified. When the scanning is started, sample motor is moved one step which leads to change the angle of prism 0.01° (θ). The detector motor is moved two step which leads to change the angle of detector 0.02° (2θ). When the scanning process is finished, each motor rotated back to lead the prism and detector back to the initial position. In the reflection box corresponding to the maximum
and minimum intensity of light. In the angle box corresponding to the angle of TIR (total internal reflection) and SPR (surface plasmon resonance). This screen of the "SPR angle scanning" tab is shown in Figure 9.

- **Filter data.** In this tab, a filter data obtained from the last SPR angle scanning. Filter method to smoothing is carried out through the "Savitzky and Golay function" from LabView software. This function is a digital filter that can be applied to a set of digital data points to increase the signal-to-noise ratio without greatly distorting the original signal by convolution. First, the polynomial order and the number of data points is specified to each side of the current data point to use for the least squares minimization. After filter process finished, a graph which smoothed is displayed. In the reflection box corresponding to the maximum and minimum intensity of light. In the angle box corresponding to the angle of TIR (total internal reflection) and SPR (surface plasmon resonance).

- **Sensorgram.** In this tab, the signal of the light received by detector graphed in real time with the x-axis as time and y-axis as reflection. First, SPR angle, duration, and time interval should be specified. When the process is started, the motor rotates to SPR angle then sampling the signal of the light every time interval until duration time run out. When the scanning process is finished, each motor rotated back to original position.

- **Motor Adjustment.** In this tab, setting the motor to adjust the position of the sensor and prism to get the position 'zero'.

- **Manual.** In this tab, contain a manual guide for operating the SPR instrument.

5. Test and result

5.1 Test using half-cylinder prism as sample

This test is intended to determine whether the angle of measurement results has been matching with the reference. References are obtained via simulation using the Winspall program and related variables of the datasheet. There are two parameters to be considered in this test, i.e., the angle of the prism when there is a phenomenon of total internal reflectance and the graph form from scanning.

The first test compared the measurement results using a manual system, an automated system and simulated from an angle of 30° to 70°. The simulation was performed based on the glass datasheet (BK7) which used to have a prism refractive index of 1.5151 when subjected to a laser beam with a wavelength of 632.8 nm. Figure 10 shows a comparison graph between manual system measurement data, automated systems, and simulations. The theoretical simulation using winspall software with prism refractive index constant parameters at 632.8 nm wavelength based study is 1.5151. The manual system measurement has same construction with automated instrument, but it is using manual rotating table despite motorized rotary stage. Manual system measurement uses manual light intensity measurement using portable photodetector and record data manually. The test results using half-cylinder prism showed the Total Internal Reflection (TIR) angle of 41.31°± 0.01°. The time taken to perform a single measurement in this test is for four minutes.

![Figure 11](image1.png)

**Figure 11.** Comparison of resonance angle measurement of gold-deposited half-cylinder prism for the manual system developed a system (Automated), and theory-based simulation.

![Figure 12](image2.png)

**Figure 12.** Sensorgram graph at SPR angle of the gold-deposited half-cylinder prism.
5.2 Test using gold-deposited half-cylinder prism
The first test was performed on a half-cylinder prism which has a thickness of 30 nm gold layer by comparing the measurement results using manual and automated SPR instruments plus theoretical simulations. Tests using manual and automated SPR instruments are done from an angle of 30° to 70°. The theoretical simulation using winspall software with gold dielectric constant parameters at 632.8 nm wavelength based study is \( \varepsilon_{\text{Au}} = -12.033 + 1.163i \) [14]. The test is done to know the difference of graph form each measurement method. Figure 11 shows graphs of manual, automated, and simulated measurements. Test results using gold-deposited half-cylinder prism showed the Total Internal Reflection (TIR) angle of 41.34°± 0.01° and SPR angle of 44.20°± 0.01°, respectively.

5.3 Real-time Test measurement using sensorgram
Real-time measurements on SPR instruments can be used to obtain sensorgrams. There are three ways to get the sensorgram, one of which is measuring the reflectance of time shift [15]. Reflectance is measured at a fixed angle. Usually, the selected angle is the SPR angle because it is a unique parameter of measurement and can also describe its refractive index. Therefore, this test aims to test the ability of SPR instruments in performing measurements in real time. Measurements were made on gold-deposited half-cylinder prism at the SPR angle every second for 1000 seconds. The result of the test shown in Figure 12 demonstrated a reflectance value that tends to be constant even if actual data is seen up and down reflectance value, but because the value of up and down is small then not visible on the graph. The reflectance value is small because the measurement angle is done at an angle of 44.20° which is the SPR angle of sample A. Due to the non-treatment of the gold layer the reflectance value remains constant.

6. Conclusion
Development of low cost and accurate homemade sensor system based on Surface Plasmon Resonance (SPR) have been successful. The result demonstrated that the developed system managed to reduce the measurement duration, data recording errors caused by human error, and easy to use. Also, the test results also concluded that the system’s measurement is repeatable and accurate.

7. Acknowledgement
This work was supported by Hibah Peningkatan Kapasitas Peneliti Dosen Muda 2017 coordinated by Directorate of Research, Universitas Gadjah Mada.

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