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Fiber-Optic Pulsed Ultraviolet Light Sensor for Defective Insulator Monitoring

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A fiber-optic pulsed ultraviolet (UV) light sensor, based on a functional polymer-coated optical fiber and butt-coupling of the waveguides, is proposed. The azobenzene polymer was prepared by mixing an azobenzene compound and an UV curing agent. The polymer was applied as a coating on one of two optical fibers and aligned in an alumina fiber ferrule by using a UV curing process. This coating was reversibly stretched by UV light, and in the coated region, the UV light along the fiber induced tensile strains. The strain induced a gap variation between the fibers that resulted in a variation in the optical coupling ratio. The coupling intensity was measured using lock-in amplification to suppress the system noises. We achieved fast detection of UV light, pulsed with a time duration of 0.1 s. This sensing technique is an initial step required to monitor instantaneous UV light in a defective insulator.

Keywords: Ultraviolet sensor, Defective insulator, Fiber-optic sensors, Azobenzene material.

I. INTRODUCTION

Ultraviolet (UV) radiation can be generated by lightning strikes and high power output; however, very weak UV light can also be detected resulting from fire. Recently, UV sensors have been used to check defective insulators by measuring the UV-light from the coronal discharge of the insulator [1–3]. The survey of the corona discharge detection case of the actual transmission and distribution facility measured the range of the count rate from 2299 /min to 4467 /min depending on the progress of the defect [4]. Therefore, on average, UV pulse detection of 0.001 to 0.002 s is required. Generally, semiconductor-based UV detectors, such as Si, ZnO, and GaN have been widely used [5–7]. However, these are difficult to install in close range of an insulator because their errors are highly dependent on electromagnetic interference (EMI). Fiber-optic UV sensors were recently proposed as a solution to this problem. A polyaniline (PAni)-coated integrated microfiber resonator, which represents a famous, highly sensitive fiber sensing element, has been reported to detect UV light [8]. The wavelength shift is linearly proportional to the UV light intensity, owing to high absorbance in the UV region and the photothermal effect of PAni. In another approach, a UV-induced stretchable fiber Bragg grating (FBG), coated with a photomechanical polymer material, such as the photoisomerization process (cis → trans status) [9] of azobenzene moiety, was recently proposed. This was a novel UV sensor, capable of a quasi-distributed measurement with a lower EMI effect [10, 11]. The sensor could be attached close to an insulator under test because it was unaffected by EMI, unlike semiconductor-based UV detectors. It also exhibited reversible length variation characteristics that changed its internal structures when exposed to UV light. The FBG-based UV sensor has many advantages; however, UV pulse radiation detection requires a pulse width significantly less than 0.02 s. UV pulse detection is used to monitor UV sparks in a defective insulator. The surface corona discharge spectrum is dependent on the voltage applied to the insulators. The UV radiation, ranging from 200 nm to 400 nm, exacerbates with an increase

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in voltage. The FBG-based UV sensor has a limitation when detecting fast UV pulses because it requires a low-speed interrogator system and data processing time. Moreover, the azobenzene material coated on the FBG is stretched by UV light, which stretches the grating of the 10 μm diameter core, surrounded by a thick cladding region of 125 μm. It is difficult to affect the UV-induced strain force of the polymer material on the core region effectively, which degrades the UV detection speed of the FBG-based UV sensors. It is also difficult to achieve a high-speed response time of less than 0.02 s with the microfiber resonator-based UV sensor, owing to the slow photothermal response of the PAni material.

In this paper, we propose a UV pulse radiation detection method with a simple fiber-optic configuration and the UV-sensitive azobenzene material. The configuration is based on two butt-coupled optical fibers, aligned by an alumina ferrule. One of the fibers was fixed with epoxy and the other was coated with an azobenzene polymer, which had a UV-induced mechanical movable effect. The azobenzene polymer functioned as a micro-actuator, controlled by UV light. The movable fiber was reversibly pushed, according to the UV irradiation on the polymer coating region. The coupling intensity of the optical fibers was subsequently changed with the UV absorption on the functional polymer. We achieved a fast UV detection response, up to 0.1 s, by use of our proposed pulsed UV sensing system.

II. EXPERIMENTS AND RESULTS

We prepared an azobenzene compound (4-Amino-1,1'-azobenzene-3,4'-disulfonic acid monosodium salt, $C_{12}H_{10}N_3NaO_6S_2$) and a UV curing agent (LS-2211, Luvantix ADM Inc.). The azobenzene and curing agent were mixed by stirring for 1 h in the ratios of 0.5 and 0.95 wt%, respectively. The preparation and properties of the polymer material are referred to in detail in Ref. [11]. We then used an alumina ferrule, which is an element of a fiber-optic connector, to align two optical fibers. The alignment configuration represents two butt-coupled waveguides. One of the fibers was fixed with epoxy and the other was coated with the azobenzene polymer, as a UV sensing part, as shown in Fig. 1. The coating length was approximately 2 cm. Index matching gel was inserted in the gap between the fibers to increase the optical coupling efficiency. The azobenzene polymer-coated fiber was moved according to the UV absorption on the polymer region, which decreased the gap and subsequently increased the coupling intensity. The coupling intensity was reversibly changed with UV light irradiation. The response of the coupling intensity was as fast as the response of the azobenzene polymer when irradiated with UV pulses.

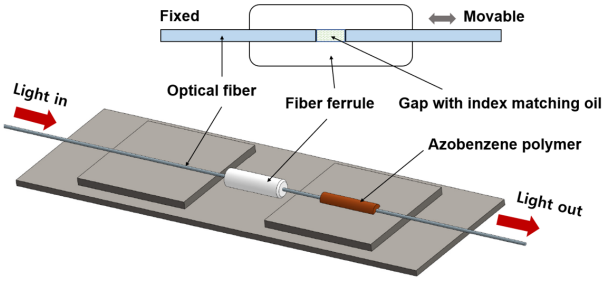

Fig. 1. (Color online) Schematic diagram of the fiber-optic pulsed UV sensor, based on fiber butt-coupling and UV-responsive azobenzene polymer.

Figure 2 shows the insertion loss of the fiber-optic UV sensor, with respect to wavelength. In the communication band, the value is averaged to –1.3 dB, which is small enough to ignore the wavelength dependence in the band. We used a laser diode (LD, SFL-1550P, Thorlabs Inc.) with a wavelength of 1556.34 nm and an insertion loss of –1.337 dB. The LD was operated at a single frequency, using an external cavity. The gaps in the sensor for the UV absence and presence were determined to be 287.82 μm and 285.44 μm, respectively. This was determined using the measured coupling ratio (T) of the sensor and the equation as the gap, $S = (2\pi n\omega^2/\lambda)\sqrt{1/T-1}$ [12], where the wavelength (λ) was 1556.34 nm, the refractive index (n) of the index matching gel was 1.458, and the mode field diameter (2ω) was 12 μm. Thus, the UV-induced gap difference was – 2.38 μm.

Even with a fast fiber-optic pulsed UV sensor, the UV-induced gap variation is very small and the subsequent variation in the coupled intensity may be difficult to distinguish from the detection system noise, such as shot and thermal noise. The noise can be minimized using

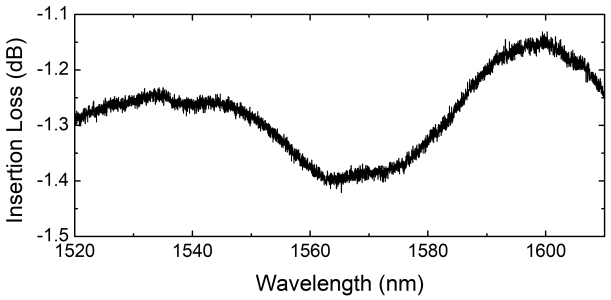

Fig. 2. Insertion loss of the fiber-optic UV sensor with respect to wavelength.

a lock-in amplification technique for high-sensitive signal detection, as shown in Fig. 3. A lock-in amplifier (SR810, Stanford Research System) launched a sinusoidal signal, with a frequency of 20 kHz, into the modulation input of the LD driver, which generated an optical signal with a modulated frequency of 20 kHz. The detected signal was also carried into an input port of the lock-in amplifier as feed-back. Through the lock-in amplification process, we achieved a highly sensitive detection signal from the pulsed, UV-induced instant gap change of the fibers in Fig. 1. Figure 4 shows the pulsed UV detection for a pulse duration of 0.2 s–results with and without the lock-in amplifier are displayed. For a proof of concept, the instantaneous UV light was generated with a UV LED (UV Engin Inc.), with a wavelength of 365 nm, and an electrically controlled optical beam shutter (SH1, Thorlabs Inc.). The exposed UV power was approximately 65 mW/cm^2. When the UV light was exposed instantaneously, we could not distinguish these events from the system noise, as illustrated in Fig. 4 (a). In this figure, the arrows represent the positions of the exposed pulsed UV light; we set a pulse interval of 60 s. However, when we applied the lock-in amplification to the pulsed UV monitoring, we could detect clearly distinguished instant pulse signals, as shown in Fig. 4(b).

We tested our proposed pulsed UV detection with pulse durations of 0.1, 0.2, 0.5, and 1.0 s, which were set with the programmable optical beam shutter as an initial stage experiment for fault detection. Figure 5 shows the pulsed UV detection results for instantaneous UV light for each time duration. The UV pulse can be clearly recognized when the UV light is exposed instantaneously on the azobenzene coating region of our proposed UV

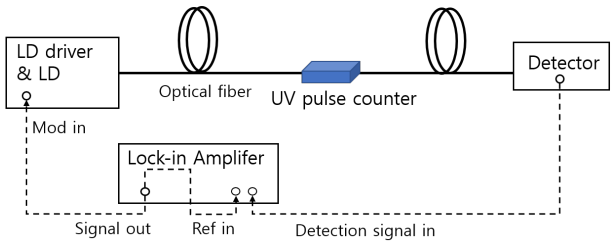

Fig. 3. (Color online) Schematic diagram of the fiber-optic pulsed UV sensing system, with the lock-in amplifier, to reduce system noises.

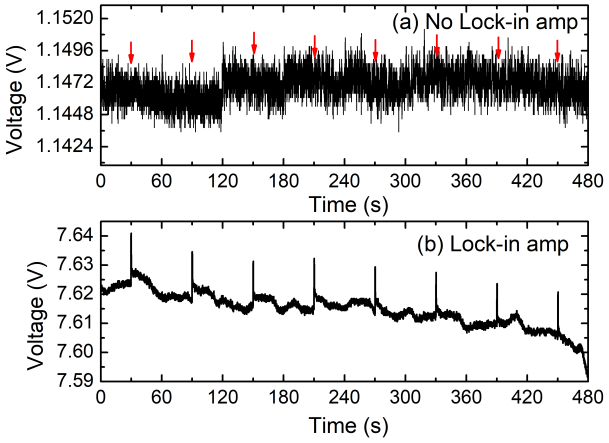

Fig. 4. (Color online) Pulsed UV detection (a) without the lock-in amplifier and (b) with the lock-in amplifier with a pulse duration of 0.2 s. Arrows in (a) represent the positions of the exposed pulsed UV light.

sensor. We recognize that the method achieves high-speed UV detection up to the response time of 0.1 s. Slow fluctuations in the detection voltages in Fig. 5 were unexpectedly observed, owing to a very small variation of the LD output power, temperature variation of the sensing elements, such as the index matching gel filled gap between the fibers, and the UV sensitive azobenzene polymer. However, this did not hinder the detection of UV sparks in a defective insulator because the variation was slow enough. To compare each instantaneous UV pulse, a single pulse from each of the trains in Fig. 5 is shown in Fig. 6. The pulse widths for set pulse durations of 0.1 s, 0.2 s, 0.5 s, and 1.0 s were determined to be 0.132 s, 0.22 s, 0.528 s, and 1.012 s, respectively. The measurement error increased with a decrease in the pulse duration. The time resolution of our measurement system was 0.044 s, as the data sampling rate was limited by the data acquisition and signal processing, thus causing the error increase for small pulse durations. High-speed acquisition and signal processing instruments can,

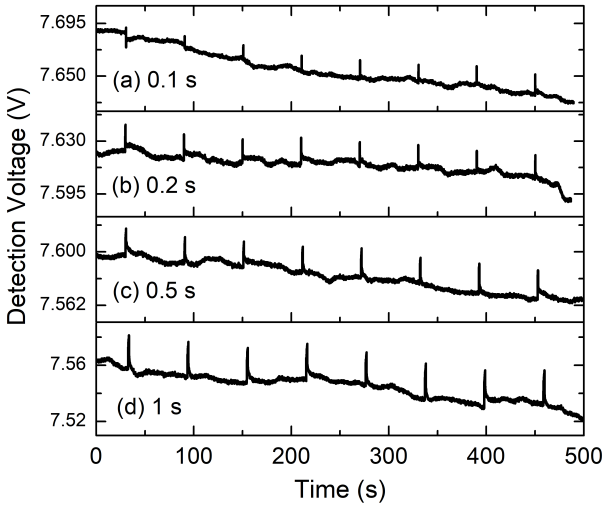

Fig. 5. Pulsed UV detection results for instantaneous UV light with time durations of (a) 0.1 s, (b) 0.2 s, (c) 0.5 s, and (d) 1.0 s.

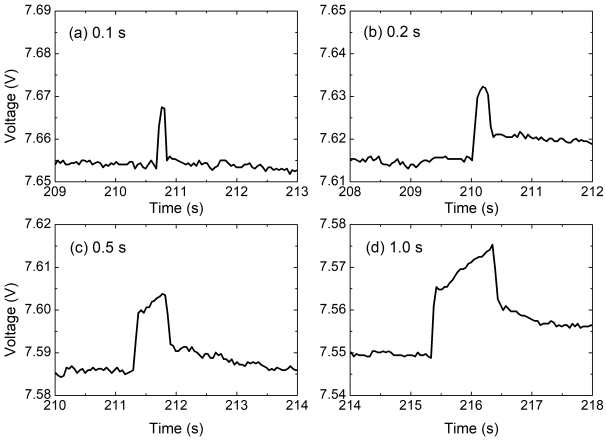

Fig. 6. Magnification of a single pulse for the trains in Fig. 5 (a)–(d).

therefore, achieve a better performance for a fast time response for pulsed UV detection.

The minimum detectable UV intensity was calculated from the data of 0.1 s in Fig. 6(a) to address the sensitivity of the sensor. The UV light intensity exposed when the shutter is opened is 65 mW/cm^2, so the maximum value of the pulse relative to the minimum value of the measured noise is obtained, and the comparison of the maximum value compared to the minimum value of the noise indicates 8.66 mW/cm^2. The UV measurement sensitivity is able to be achieved by modifying Azobenzene material compositions.

In addition, we observed both a fast and slow increase of the detection voltage for the UV pulse of 1.0 s duration in Fig. 6(d). When the UV light turned on, the voltage changed rapidly and then proceeded to change more slowly. The voltage also rapidly dropped when UV light turned off and it slowly recovered back to the original voltage. In a previous paper, we have reported on the UV light reaction and photothermal effect of an azobenzene-coated FBG for a UV sensor, which resulted in a fast and slow response, respectively [10]. In Fig. 6, the slow variation region for the photothermal effect decreased with a decrease in the pulse duration because the photothermal effect does not stretch the azobenzene coating region in fast UV inputs; the photoisomerization process of cis → trans is the dominant mechanism to stretch the polymer by UV light. The voltage changes for the isomerization in Fig. 6 were measured at 0.0144 V, 0.0147 V, 0.0141 V, and 0.0166 V for the pulse durations of 0.1 s, 0.2 s, 0.5 s, and 1.0 s, respectively. These values are similar owing to the fast UV response of photoisomerization of the azobenzene polymer. It is expected that the measurement sensitivity, based on the photoisomerization, is almost constant, even for pulse durations less than 0.1 s.

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REFERENCES

[1] T. Chen, H. -Y. Liu, C. -P. An and W. -Z. Tang, 2008 World Automation Congress , 1 (2008).

[2] K. -M. Shong, Y. -S. Kim and S. -G. Kim, 2007 IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives , 462 (2007).

[3] Y. Hu, K. Liu, *Inspection and Monitoring Technologies of Transmission Lines with Remote Sensing, first ed.* (Academic Press, 2017), Chap. 4.

[4] J. -M. Kim, J. -I. Yoo and S. -D. Kim, Journal of Electrical World Monthly Magazine , 42 (2007).

[5] T. Dankovic *et al.*, 2000 22nd International Conference on Microelectronics. Proceedings (Cat. No.00TH8400) **2**, 585 (2000).

[6] Y. Li *et al.*, 2006 8th International Conference on Solid-State and Integrated Circuit Technology Proceedings , 947 (2006).

[7] B. Poti *et al.*, Electron. Lett. **39**, 1747 (2003).

[8] K. Lim *et al.*, IEEE Sens. J. **13**, 2020 (2013).

[9] L. Hines, K. Petersen, G. Z. Lum and M. Sitti, Adv. Mater. **29**, 1603483 (2017).

[10] H. -K. Kim, W. Shin and T. -J. Ahn, IEEE Photonics Technol. Lett. **22**, 1404 (2010).

[11] G. -S. Seo, H. -T. Cho, O. -R. Lim and T. -J. Ahn, Sens. Actuators A Phys. **283**, 169 (2018).

[12] M. Yasin, *Optical fiber communications and devices, Ch.11 (by M. Kihara, NTT Inc.),* (InTech, 2012), p. 241.