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Ultraviolet Light Sensor Based on an Azobenzene-polymer-capped Optical-fiber End

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We propose a simple ultraviolet (UV) sensor consisting of a conventional single-mode optical fiber capped with an azobenzene-moiety-containing polymer. The UV light changes the dimensions of the azobenzene polymer, as well as the refractive index of the material. Incident light with a wavelength of 1550 nm was reflected at the fiber/polymer and polymer/air interfaces, and interference of the reflected beams resulted in spectral interference that shifted the wavelength by 0.78 nm at a UV input power of 2.5 mW/cm^2. The UV sensor's response to wavelength is nonlinear and stable. The response speed of the sensor is limited by detection noise, which can be improved by modifying the insertion loss of the UV sensor and the signal-to-noise ratio of the detection system. The proposed compact UV sensor is easy to fabricate, is not susceptible to electromagnetic interference, and only reacts to UV light.

Keywords : Ultraviolet, Optical sensor, Optical fiber sensor, Azobenzene
OCIS codes : (040.7190) Ultraviolet; (060.3735) Fiber Bragg gratings; (060.2370) Fiber optics sensors; (160.5335) Photosensitive materials

I. INTRODUCTION

Ultraviolet (UV) light has been widely used in medical treatments, defect detection, water purification, UV curing, and printing [1-5]. Thus, UV sensors are necessary for reducing UV-related accidents for safety in these fields. In addition, UV light is emitted by electric leakage or similar situations in lightning strikes [6] and high-power generation [7], and early detection of UV light can prevent the development of a fire [8]. Moreover, monitoring corona discharge, which includes UV radiation, is important for real-time inspection of electrical faults in external power insulation systems [7, 9].

Semiconductor-element-based UV sensors [10] are likely to suffer malfunctions in high-voltage fields. UV cameras are popular for visually inspecting UV leakage in high-power transmission lines and insulators [11]. However, these conventional UV sensors cannot easily be used for real-time monitoring and remote measurements. In particular, these methods have lower measurement reliability because they have difficulty in close-proximity measurements, due to their high sensitivity to electromagnetic interference (EMI). Fiber-optic UV sensors have been developed, using a UV-induced index-controllable polymer on a side-polished fiber and optical waveguides [12, 13]. These sensors are less sensitive to EMI effects, but multipoint measurements cannot be realized.

In previous studies, a UV-induced-stretchable fiber Bragg grating (FBG) has been coated with a photomechanical polymer material to produce a UV sensor that is capable of real-time monitoring and multipoint simultaneous measurements, and is less sensitive to EMI [14-17]. Rapid and reversible photoresponsive materials have been reported [18-20]; specifically, polymer-blend films consisting of poly(vinylether) with an azobenzene-moiety side chain and polycarbonate matrix [19] have been proposed as photo-induced shape-memory polymers. The blend films rapidly elongate and recover under UV-induced tensile stress, due

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to frequent *trans-cis* cycling isomerization of the azobenzene moieties. Thus, an FBG coated with an azobenezene-containing polymer material has reversible length-change characteristics that vary with exposure to UV light [14]. Though the FBG-coated UV sensor has many useful characteristics, it is complicated to fabricate.

In this study, we propose a simple UV sensor consisting of only a cleaved optical fiber coated with azobenzene polymer, which induces a spectral interference pattern of reflected light in a multiple-reflection scheme. Unlike the complicated process for fabricating the azobenzene-coated FBG sensor, the azobenzene polymer is coated on the end face of the fiber, in a process similar to that used for thin films. The phase of the spectral interferogram depends on the index and thickness of the azobenzene layer. In the presence of UV light, the volume of the layer expands due to the *trans-cis* isomerization of the azobenzene moieties, and the index of the material increases. Consequently, the phase is shifted to a longer wavelength. We were able to detect the presence of UV light by detecting the phase change.

II. MEASUREMENT PRINCIPLE

Multiple light reflections can occur within the thin-film coating of a transparent material, called an optical coating, over a substrate (*e.g.* semiconductor or glass). Using this principle, we monitor UV light from the environment based on the multiple-reflection scheme illustrated in Fig. 1, where light from a coherent source traveling in an optical fiber's core with refractive index n_1 is incident on an azobenzene-polymer layer with index n_2, and on air with index n_3. The multiple induced reflections and their behavior are almost identical to those in a Fabry-Perot optical cavity when multiple interferences appear; however, the azobenzene layer has a high optical loss α, compared to the transparent coating of a conventional thin film.

We let d be the azobenzene layer thickness, and assume normal incidence of the light. The phase change for traversing the layer thickness twice is $\phi = 2(2\pi/\lambda)n_2 d$, where λ is the free-space wavelength. To consider both the phase change and optical loss α during traversal, the wave must be multiplied by $e^{-\alpha(2d)-j\phi}$. Optical loss here consists

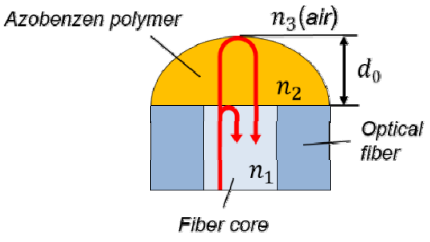


FIG. 1. Multiple reflections of an optical fiber capped with azobenzene polymer.

of absorption and scattering by the azobenzene-polymer layer, as well as recoupling of the light reflected from the layer/air interface to the fiber core. Considering multiple reflections as a geometric series, the reflection coefficient r can be obtained as [21]

$$r = \frac{r_1 + r_2 \exp(-2\alpha d - j\phi)}{1 + r_1 r_2 \exp(-2\alpha d - j\phi)} \tag{1}$$

where $r_1 = (n_1 - n_2)/(n_1 + n_2)$ and $r_2 = (n_2 - n_3)/(n_2 + n_3)$. The reflectance R is obtained by letting $R = |r|^2$:

$$R = \frac{r_1^2 + r_2^2 \exp(-4\alpha d) + 2r_1 r_2 \exp(-2\alpha d)\cos\phi}{1 + r_1^2 r_2^2 \exp(-4\alpha d) + 2r_1 r_2 \exp(-2\alpha d)\cos\phi} \tag{2}$$

When $n_1 > n_2 > n_3$, the reflectance R reaches its maximum for $\phi_m = 2(2\pi/\lambda)n_2 d = 2m\pi$, $m = 1, 2, \cdots$. Hence, a UV-induced wavelength shift of the sensor can be obtained via the derivative of the wavelength, index, and thickness:

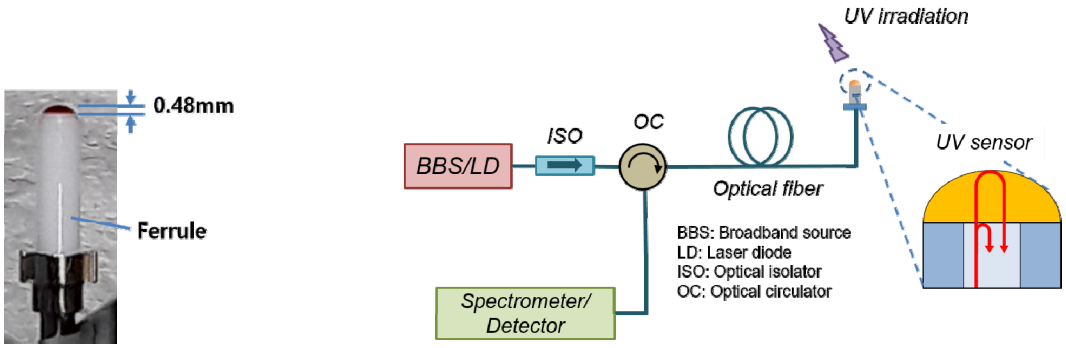
$$\triangle\lambda = 2(\triangle n_2 d + n_2 \triangle d) \tag{3}$$

The index and volume of the azobenzene polymer coating change with UV exposure, due to the *trans-cis* isomerization of the material. As a result, the azobenzene-incorporated fiber sensor can be used as a novel UV sensor featuring simple fabrication and stable, accurate performance.

III. EXPERIMENTS AND RESULTS

We used 4-(Dimethylamino)azobenzene-4′-sulfonyl chloride ($C_{14}H_{14}ClN_3O_2S$ Sigma-Aldrich Inc.) for the photofunctional material, with LS2211 curing agent (Luvantix ADM), which is conventionally used for secondary coatings on glass optical fibers. The azobenzene compound and curing agent were mixed at 0.5 and 0.95 wt% and stirred for 1 hr. In our simple fabrication technique, we dropped the mixed material on the end of a single-mode optical fiber (core and cladding diameters of 8 and 125 μm respectively) that was vertically fixed in a mount. The material was cured for 40 min using a UV light-emitting diode (LED) (LZ1-00UV00, LED Engin Inc.) with a wavelength of 365 nm and output power of 1200 mW. Figure 2(a) shows the completed UV sensor with a ferruled single-mode optical fiber capped with photoreactive material. The coating thickness was about 0.48 mm, and the ferrule length was 4.15 cm. This UV sensor requires only a small amount of functional polymer, which reduces the cost of the device. Figure 2(b) illustrates the experimental setup for the UV sensor. The round-trip measurement configuration enables remote monitoring of the sensing point.

First, we measured interference of multiple reflections in the UV sensor. An amplified spontaneous emission (ASE)



(a) (b)

FIG. 2. (a) The actual UV sensor with a ferrule and (b) diagram of the experimental setup.

light source with a central wavelength of 1550 nm and a spectral width greater than 50 nm was used for the broadband light source (BBS). The optical spectrum was acquired by an optical-spectrum analyzer. The broadband light propagated through the optical isolator and optical circulator to the UV sensor. The light was reflected at the interface of the fiber core and material, as well as at that of the material and air, which resulted in spectral interference between multiple reflections. Figure 3 shows the input BBS and interfered spectra. A distinct sinusoidal oscillation in the wavelength domain was observed, with a peak-to-peak amplitude of approximately 8 dB and a period of 1.6 nm. In comparison with the BBS spectral intensity, the sensor insertion loss was about 30 dB, because of optical absorption and scattering of the polymer material, small reflectance at the interfaces, and recoupling loss to the optical fiber.

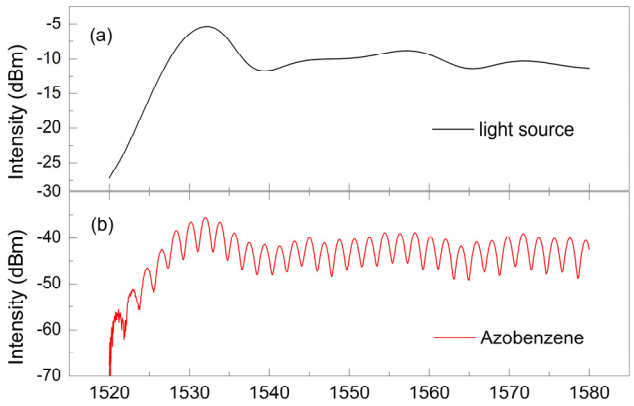
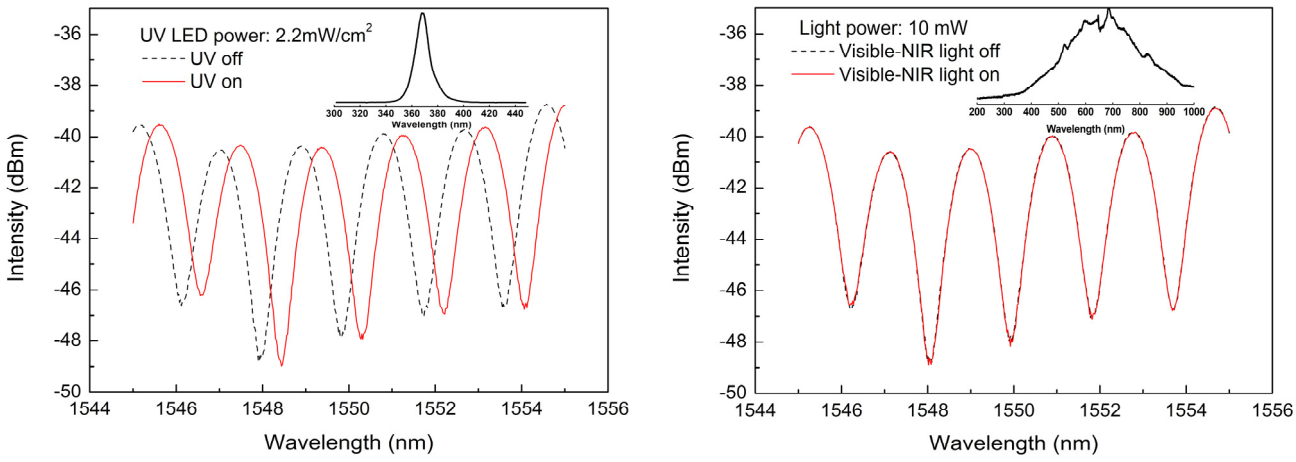


FIG. 3. (a) Spectrum of the broadband light source, and (b) spectrum of the multiple reflections from the azobenzene-polymer-coated fiber's end.

In Fig. 3(b) the phase increased with increasing polymer index and coating thickness, according to Eq.(3). In Fig. 4(a) we confirmed the phase change of the interference pattern in the presence of UV light at room temperature. The wavelength shift was about 0.38 nm when the UV LED power and center wavelength were 2.2 mW/cm^2 and 365 nm respectively. The UV LED's spectrum is given in the inset of Fig. 4(a). On the other hand, the wavelength does not shift under a 10-mW visible light (SLS203L,



(a) (b)

FIG. 4. Photoinduced phase changes of the interference pattern by (a) UV LED and (b) a visible-to-near-infrared light source.

Thorlabs Inc.), as shown in Fig. 4(b), with the visible light's spectrum given in the inset. Thus, the azobenzene-polymer-based UV sensor only operated under UV light exposure.

Figure 5 shows the average UV-induced wavelength shift and standard deviation with respect to the UV LED intensity, after repeated measurements. The nonlinear spectral response occurred because the phase shift was caused by changes in both index and thickness of the azobenzene layer [12, 14]. The wavelength shift reached 0.1 nm at 0.5 mW/cm^2 and 0.35 nm at 2.2 mW/cm^2. In Fig. 4(a), the slope of the linear region was about 8 dB/nm, indicating that the power of reflected light from the sensor was 8 dB when the wavelength shifted 1 nm. Thus the proposed UV sensor can be used to detect UV radiation by monitoring the shift in peak wavelength of the interferogram, or the power change of the reflected light.

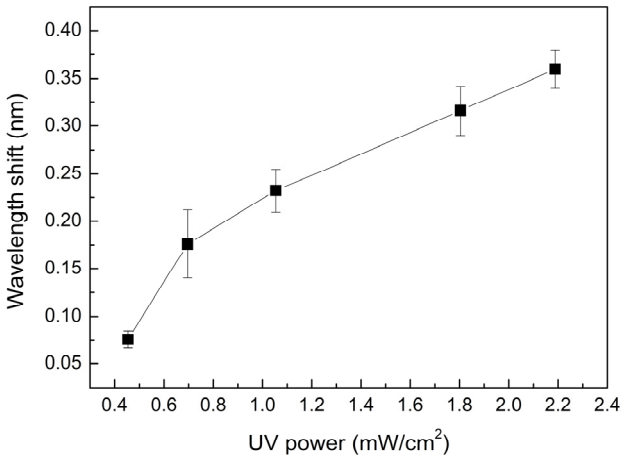
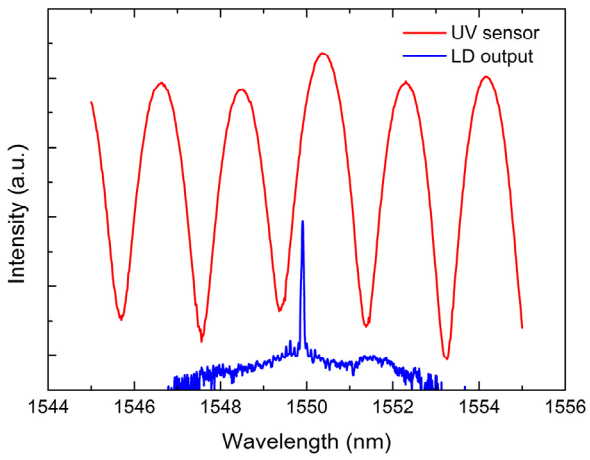


FIG. 5. UV-induced wavelength shift of the sensor, with respect to UV intensity.

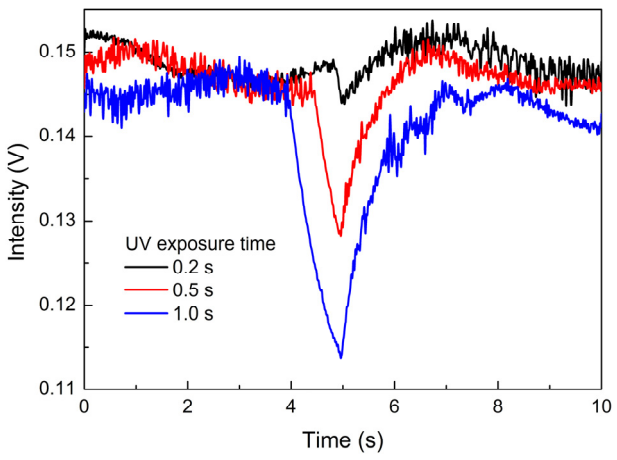
Spectrum analysis for sensing applications often requires expensive equipment, presents low data acquisition and treatment rates, and the measurement system is difficulty to move for field tests. However, measuring the sensor's UV-induced spectral response in time with a laser diode (LD) and optical detector (Fig. 2) can overcome these problems. The LD's primary wavelength is located in the linear region of the UV sensor's spectral response, as shown in Fig. 6(a). The LD (SFL1550S, Thorlabs Inc.) had a single wavelength of 1550 nm, and an optical power of 28 mW. The reflected light intensity from the UV sensor decreased with the wavelength shift in the presence of UV light. Figure 6(b) shows the decreased intensity of the reflected light under UV, and its recovery when UV was removed. We used an optical shutter (SH05, Thorlabs Inc.) for the temporal response measurement, and a UV LED with a central wavelength of 365 nm and power of 2.2-mW/cm^2. The shutter open times were 0.2, 0.5, and 1.0 s. Detecting UV in the sensor results in an abrupt decrease in the intensity of output light from the optical measurement system. When the shutter speed was less than 0.2 s, the sensor's response was not easily distinguished from the signal noise of the detector, because of the large insertion loss. Decreasing the sensor's insertion loss must be considered, by improving the azobenzene material for low optical absorption and scattering, modifying the optical coupling element, or using a highly sensitive detection scheme (*i.e.* balanced detection).

IV. CONCLUSION

We have proposed a simple UV sensor based on a conventional optical fiber coated with a thin layer of azobenzene-moiety-containing polymer. The incident light was reflected at the fiber/polymer and polymer/air interfaces,



(a)



(b)

FIG. 6. (a) LD output at a wavelength matched to the linear region of the UV sensor's spectral response and (b) temporal responses of the UV presence for shutter open times of 0.2, 0.5, and 1.0 s.

and the reflected light interfered, resulting in spectral interference. The wavelength was shifted by 0.35 nm at a UV input power of 2.2 mW/cm^2. We further demonstrated that the response speed of the UV sensor was 0.2 s, which can be improved by modifying the insertion loss of the UV sensor and the signal-to-noise ratio of the detection system. The proposed compact UV sensor has the advantages of easy fabrication with low material requirements and low susceptibility to EMI in the round-trip sensor configuration. Moreover, we confirmed that the sensor only reacted to UV light, not to visible-NIR light (500~900 nm). Because of its advantages, the proposed sensor will be useful for monitoring the presence of UV light in many contexts, such as high-voltage insulators, high-power transmission lines, and instruments using high-power UV light.

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REFERENCES

1. R. T. Kashiwabuchi, F. R. S. Carvalho, Y. A. Khan, D. de Freitas, A. S. Foronda, F. E. Hirai, M. S. Campos, and P. J. McDonnell, "Assessing efficacy of combined riboflavin and UV-A light (365 nm) treatment of Acanthamoeba Trophozoites," Invest. Ophthalmol. Visual Sci. **52**, 9333-9338 (2011).
2. R. Simpson, *Lighting Control: Technology and Applications* (Burlington, MA: Focal Press, 2003).
3. B. Srikanth, "Recent advancements in UV technology yield enhanced TOC reduction performance," Ultrapure Water **15**, 40-46 (1998).
4. S. P. Pappas, *UV Curing: Science and Technology, Vol. 2* (Technology Marketing Corporation, 1985).
5. R. Zhou and X. Tian, "Design and simulation of UV LED light source for curing rotary printing ink," J. Control Eng. Technol. **3**, 153-157 (2013).
6. Y. Hu and K. Liu, *Inspection and Monitoring Technologies of Transmission Lines with Remote Sensing* (San Diego, CA: Academic Press, 2017).
7. A. R. Pauchard, D. Manic, A. Flanagan, P. A. Besse, and R. S. Popovic, "A method for spark rejection in ultraviolet flame detectors," IEEE Trans. Ind. Electron. **47**, 168-174 (2000).
8. K.-M. Shong, Y.-S. Kim, and S.-G. Kim, "Images detection and diagnosis of corona discharge on porcelain insulators at 22.9 kV D/L," in *Proc. IEEE International Symposium on Diagnositics for Electric Machines* (Poland, Sept. 2007), pp. 462-466.
9. M. A. Uman, *The Lightning Discharge* (Orlando, FL: Academic Press, 1987).
10. O. M. Nayfeh, S. Rao, A. Smith, J. Therrien, and M. H. Nayfeh, "Thin film silicon nanoparticle UV photodetector," IEEE Photon. Technol. Lett. **16**, 1927-1929 (2004).
11. M. K. W. Stranges, S. U. Haq, and D. G. Dunn, "Black-out test versus UV camera for corona inspection of HV motor stator endwindings," IEEE Trans. Ind. Appl. **50**, 3125-3140 (2014).
12. K. T. Kim, N. I. Moon, and H.-K Kim, "A fiber-optic UV sensor based on a side-polished single mode fiber covered with azobenzene dye-doped polycarbonate," Sens. Actuators A **160**, 19-21 (2010).
13. S.-W. Jang, S.-J. Son, D.-E. Kim, D.-H. Kwon, S.-H. Kim, Y.-H. Lee, and S.-W. Kang, "UV-sensitive photofunctional device using evanescent field absorption between SU-8 polymer optical waveguide and photochromic dye," IEEE Photon. Technol. Lett. **18**, 82-84 (2006).
14. H.-K. Kim, W. Shin, and T.-J. Ahn, "UV sensor based on photomechanically functional polymer-coated FBG," IEEE Photon. Technol. Lett. **22**, 1404-1406 (2010).
15. D.-S. Choi, H.-K. Kim, and T.-J. Ahn, "The study of thermal effect suppression and wavelength dependence of azobenzene-coated FBG for UV sensing application," Korean J. Opt. Photon. **22**, 67-71 (2011).
16. W. Y. Kim, C.-Y. Kim, H.-K. Kim, and T.-J. Ahn, "Improving the sensitivity of an ultraviolet optical sensor based on a fiber Bragg grating by coating with a photo-responsive material," Korean J. Opt. Photon. **26**, 83-87 (2015).
17. G.-S. Seo and T.-J. Ahn, "Protection method for diameter-downsized fiber Bragg gratings for highly sensitive ultraviolet light sensors," Curr. Opt. Photon. **2**, 221-225 (2018).
18. A. Lendlein, H. Jiang, O. Jünger, and R. Langer, "Light-induced shape-memory polymers," Nature **434**, 879-882 (2005).
19. H.-K. Kim, X.-S. Wang, Y. Fujita, A. Sudo, H. Nishida, M. Fujii, and T. Endo, "A rapid photomechanical switching polymer blend system composed of azobenzene-carrying poly(vinylether) and poly(carbonate)," Polymer **46**, 5879-5883 (2005).
20. S. Tanaka, H.-K. Kim, A. Sudo, H. Nishida, and T. Endo, "Anisotropic photomechanical response of stretched blend film made of polycaprolactone-polyvinyl ether with azobenzene group as side chain," Macromol. Chem. Phys. **209**, 2071-2077 (2008).
21. S. O. Kasap, *Optoelectronics and Photonics: Principles and Practices* (Pearson, 2013).