Tapered Plastic Optical Fiber Coated With HEC/PVDF for Measurement of Relative Humidity

A simple humidity sensor is proposed and demonstrated using a tapered plastic optical fiber (POF) as a probe. Its operation is based on intensity modulation technique using a tapered POF probe coated with a polymer blend of hydroxyethylcellulose/polyvinylidenefluoride (HEC/PVDF) composite that acts as the humidity sensitive cladding. The sensor is fabricated using an etching method and has a waist diameter of 0.45 mm and tapering length of 10 mm. As the relative humidity varies from 50% to 85%, the output voltage of the sensor increases linearly from 0.32 to 1.25 mV. The HEC/PVDF composite-coated sensor exhibits a sensitivity of 0.023 mV/% with a slope linearity of . The sensitivity of HEC/PVDF composite-coated cladding toward humidity stems from its ability to swell as humidity increases in the atmosphere resulting in a drop in its refractive index below that of the core and thus allowing more light to be transmitted through the tapered fiber.

This paper appears in: Sensors Journal, IEEE, Issue Date: Dec. 2013, Written by: Batumalay, M.; Lokman, A.; Ahmad, F.; Arof, H.; Ahmad, H.; Harun, S.W.

SECTION I
INTRODUCTION

OPTICAL fibers have been used for various applications ranging from transmission medium, which covers a wide spectral range and sensors. Research in fiber sensor development is expanding and many new applications have been introduced such as in sensing and monitoring humidity, gases, vapours, chemical substances, biosignals, medical and control processes, industrial automation and others [1], [2], [3], [4], [5], [6]. Recently, tapered optical fibers have attracted much interest especially for sensing applications [2]. An optical fiber becomes more sensitive to its surrounding when it is tapered due to the enhanced power of its evanescent wave (EW) in the cladding. Interest in tapered multimode plastic fiber has also increased because of the fiber's superior mechanical strength and ease of manufacturing.

Recently, many EW based sensors have been proposed and demonstrated for humidity measurement. For instance, Muto *et al.* demonstrated humidity sensors which are based on reversible absorption of water (H_2O) from the ambient atmosphere into a porous thin-film interferometer that sits on the tapered fiber. The water absorbed changes the refractive index of the thin films and subsequently transforms the lossy fiber into a light guide. Humidity sensing was also demonstrated using a tapered fibre with agarose gel [10]. Corres *et al.* demonstrated a similar humidity sensor based on nanostructured films, which were deposited onto tapered fibres using the ionic self-assembled monolayer (ISAM) deposition technique [11], [12]. In another scheme, a side-polished optical fibre with a humidity sensitive overlay is used to construct a humidity sensor. Gaston *et al.* [13], [14] proposed a humidity sensor based on a single mode, side-polished fibre with a PVA overlay. Such a sensor was created by means of polishing the flat surface parallel to the fibre axis in order to remove the cladding. Side polishing can be realised by first immobilising the optical fibre in a rigid material, forming a rectangular block with the fibre extending out from the two end faces of the block orthogonal to the fibre axis. The advantage of this scheme is that the sensing element can be fabricated using inexpensive components and a variety of coating materials can be deposited onto the flat surface of the fibre block. However, the fabrication procedure is very time consuming, dependent upon the design of the fibre block and has limited exposed interaction length.

As mentioned earlier, tapered optical fibers have gained much popularity in various sensing applications [15], [16], [17] due to its high sensitivity. Compared to silica based fiber, plastic optical fibers (POFs) possess several advantages such as ease of handling, mechanical strength, disposability and easy mass production of components and system [2]. In this paper, tapered POF is coated by a polymer blend of hydroxyethylcellulose/polyvinylidenefluoride (HEC/PVDF) composite to sense the change in relative humidity. The coating of the tapered fiber changes its optical properties in response to an external stimulus. The measurement is based on intensity modulation technique where the output voltage of the transmitted light is investigated for changes in relative humidity.

SECTION II
EXPERIMENT

For the preparation of HEC/PVDF, 1 g of PVDF powder $(\mathrm{Mw}=275,000)$ was dissolved in 120 ml dimethyl formamide (DMF) at the 90°C in water bath. The solution of PVDF was cooled down to room temperature, and then 4 g of hydroxyethyl cellulose (HEC) was added to the solution. The mixed solution was continuously stirred at room temperature for about 10 hours in order to get a completely homogenous solution as described by Muto *et al.* (7). Fig. 1(a) and (b) show a sample of hydroxyethylcellulose/polyvinylidenefluoride (HEC/PVDF) composite solution and its microscopic image respectively.

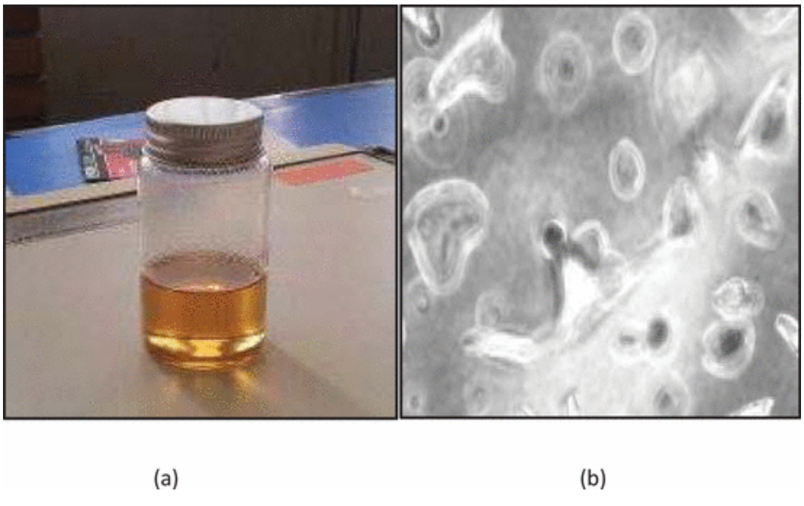

Fig. 1. Image of (a) hydroxyethylcellulose/polyvinylidenefluoride (HEC/PVDF) composite, (b) microscopic image of hydroxyethylcellulose/polyvinylidenefluoride (HEC/PVDF) composite.

The linear type of tapered POF was then prepared using acetone, de-ionized water and sand paper in accordance with chemical etching technique. The POF has an overall cladding diameter of 1 mm, a numerical aperture of 0.51 and an acceptance angle of 61°. The refractive index of the core and cladding are 1.492 and 1.402 respectively. The acetone was applied to the POF using a cotton bud and neutralized with de-ionized water. The acetone reacted with the surface of the polymer to form milky white foam on the outer surface of the cladding which was then removed by the sand paper. This process was repeated until the tapered fiber has a stripped region waist diameter of 0.45 mm. It is mentioned by Beres *et al.* that tapered fibers with waist diameters in the range of 0.40 mm to 0.50 mm showed good sensitivity to refractive index variation whereas those with waist diameters above 0.55 mm and below 0.30 mm did not demonstrate substantial sensitivity [18]. The total length of the tapered fiber for this section was fixed at 10 mm. Finally, the tapered POF was cleansed again using the de-ionized water.

Both ends of the POF were held and straightened on translation stages to deposit the HEC/PVDF onto the tapered fiber. In the process, the prepared HEC/PVDF composite solution was slowly dropped onto the tapered region of the fiber using syringe and left to dry for 48 hours. Fig. 2(a) and (b) show the microscope images of the original un-tapered and tapered POF, which have a cladding diameter of 1 mm and 0.45 mm respectively. Fig. 2(c) shows the tapered fiber coated with HEC/PVDF composite.

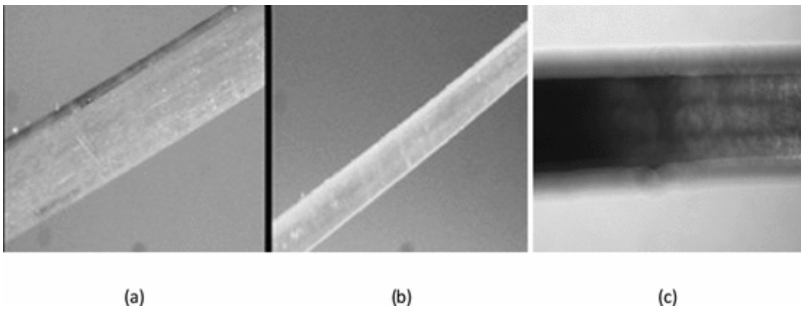

Fig. 2. Microscopic images of (a) un-tapered POF (with diameter of 1 mm), (b) Tapered POF (with diameter of 0.45 mm) and (c) Tapered POF with HEC/PVDF composite.

Fig. 3 shows the experimental setup for the proposed sensor to detect change in relative humidity using the fabricated tapered POF with and without HEC/PVDF composite. The setup consists of a light source, an external mechanical chopper, the proposed sensor, 1365 data logging humidity-temperature meter, a highly sensitive photo-detector, a lock-in amplifier and a computer. The input and output ports of the tapered POF are connected to the laser source and photo-detector, respectively. The light source used in this experiment is a He-Ne laser operating at a wavelength of 633 nm with an average output power of 5.5 mW. It was chopped at a frequency of 113 Hz by a mechanical chopper to avoid the harmonics from the line frequency, which is about 50 to 60 Hz. The He-Ne light source was launched into the tapered POF placed in a sealed chamber with a dish filled with saturated salt solution. The output light was sent into the silicon photo-detector (818 SL, Newport) to be converted into electrical signal. Then the electrical signal together with the reference signal from the mechanical chopper were fed into the lock-in amplifier (SR-510, Stanford Research System). Finally, the output from the lock-in amplifier was delivered to a computer through an RS232 port interface and the signal was processed using Delphi software. The reference signal from the chopper was matched with the input electrical signal from the photo-diode. This makes a very sensitive detection system that will remove the noise generated by the laser source, photo-detector and the electrical amplifier in the photo-detector. In the experiment, the performance of the proposed sensor was investigated for various changes in relative humidity ranging from 50% to 80% using 1365 data logging humidity-temperature meter.

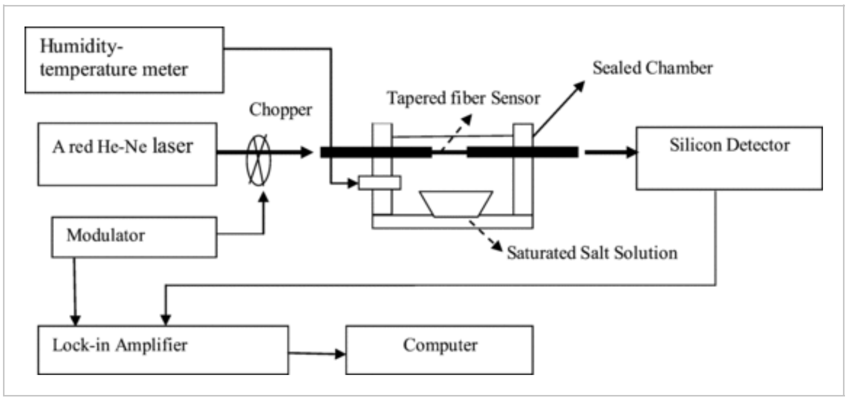

Fig. 3. Experimental setup for the proposed relative humidity sensor using a tapered POF without and with HEC/PVDF composite.

SECTION III
Results and Discussions

Fig. 4 shows the variation of the transmitted light from the tapered POF against the relative humidity for fiber with and without HEC/PVDF composite deposited onto the tapered region. The change in the intensity of the transmitted light of the HEC/PVDF composite on tapered fiber increases with relative humidity in a quadratic manner. The adjusted R-square value or the coefficient of the determination is the measure of the goodness of fit which is 0.9869. The considerably high values of the adjusted R-square allow the prediction of unknown relative humidity by the model. This is opposed to the trend demonstrated by the bare fiber where the output remains constant despite the increase of relative humidity. The humidity sensitive layer of the composite has an RI value which is higher than that of the core in dry state. This situation creates a lossy waveguide and as the cladding layer hydrates, the RI value falls below that of the core and increases the intensity of light propagating through the core. Fig. 5 depicts the output voltage from the photo-detector which shows that the transmitted light intensity linearly increases as the relative humidity rises from 55% to 80%. The bare fiber (without HEC/PVDF) has a sensitivity of 0.0034 mV/% with a slope linearity of more than 94.71% and limit of detection of 45.45%. Meanwhile the probe with the HEC/PVDF composite produces a better sensitivity of 0.0231 mV/% with a better slope linearity of more than 99.65% and a limit of detection of 5.75%. The lower limit of detection for the probe with HEC/PVDF shows that the system is more efficient. The limit of detection is calculated by dividing the standard deviation with the sensitivity.

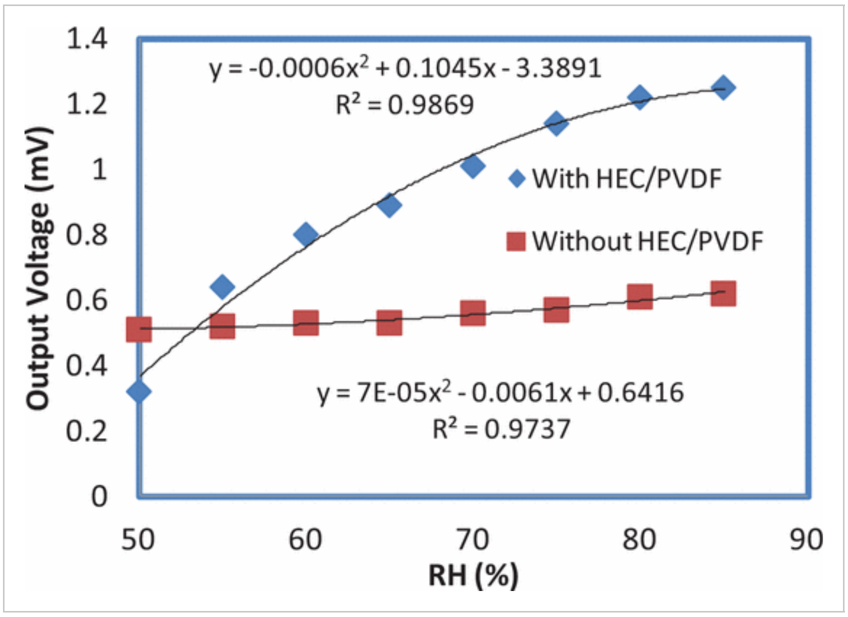

Fig. 4. Output voltage against RH for the proposed tapered POF based sensor with and without HEC/PVDF composite.

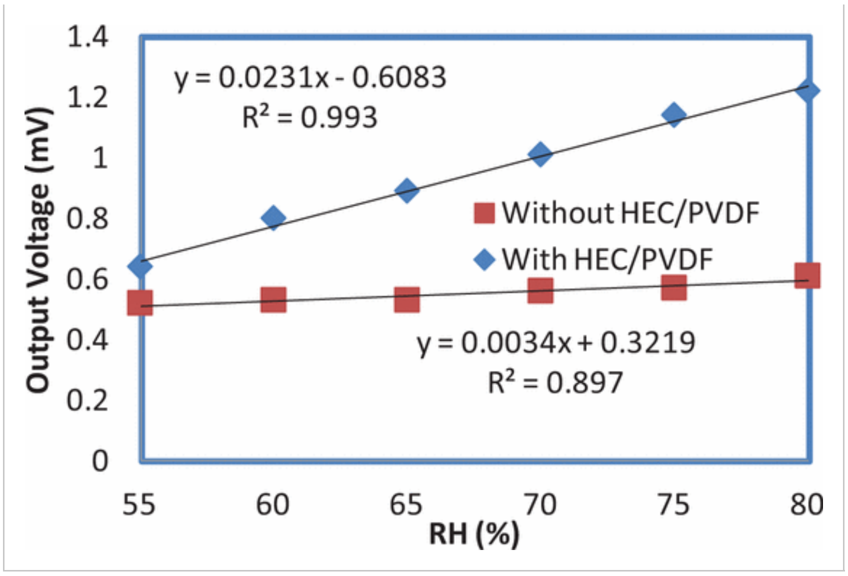

Fig. 5. Performance of Humidity Sensor with and without HEC/PVDF within the relative humidity range from 55% to 80% composite.

The performance characteristic of the proposed sensor is summarized in Table I. Overall, the sensor is observed to be sufficiently stable with a standard deviation of 0.133 mV for POF probe with HEC/PVDF composite as recorded in time duration of 100 second. Throughout the experiment, the corresponding output voltage was measured by a lock-in amplifier which provided accurate measurements even though the signal was relatively very small compared to noise. Furthermore, a well-regulated power supply is used for the red He-Ne laser and this minimizes the fluctuation of source intensity. These results show that the proposed sensor is suitable for measuring relative humidity in real time.

Performances	With HEC/PVDF	Without HEC/PVDF
Sensitivity	0.0231mV/%	0.0033mV/%
Linearity	96.72%	96.54%
Std deviation	0.133mV	0.1509mV
Limit of detection	5.75%	45.45%

TABLE I Performance of the Proposed Sensor

SECTION IV
Conclusion

A simple humidity sensor has been proposed and demonstrated using a tapered POF coated with HEC/PVDF composite. The tapered POF was fabricated by etching method using acetone, sand paper and de-ionized water to achieve a waist diameter of 0.45 mm and tapering length of 10 mm. As the relative humidity increases from 55% to 80%, the ouput voltage of the sensor increases linearly with a sensitivity of 0.0231 mV/% and a linearity of more than 99.65%. The limit of detection is calculated to be 5.75%. The rise in humidity level reduces the effective refractive index of the composite cladding thus allowing more light to be transmitted. The proposed sensor presents a stable and efficient humidity detector with numerous advantages such as simplicity of design, low cost of production, higher mechanical strength and ease of handling over similar sensors that use silica fiber optic. In summary, the results show that the HEC/PVDF coated fibre reacts to change in humidity by altering its conductance and therefore demonstrates its suitability as a relative humidity sensors.

FOOTNOTES

This work was supported in part by the MOHE High Impact Research under Grant D000009-16001. The associate editor coordinating the review of this paper and approving it for publication was Dr. Anna Grazia Mignani.

M. Batumalay, A. Lokman, and S. W. Harun are with the Department of Electrical Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia (e-mail: malathy.batumalay@newinti.edu.my; lokman_asiah@yahoo.com; swharun@um.edu.my).

F. Ahmad is with the Department of Electrical Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia, and also with the Department of Electrical Engineering, Universiti Teknologi Malaysia, Kuala Lumpur 54100, Malaysia (e-mail: fauzan.se@gmail.com).

H. Arof and H. Ahmad are with the Photonics Research Center, University of Malaya, Kuala Lumpur 50603, Malaysia (e-mail: ahamzah@um.edu.my; harith@yahoo.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

REFERENCES

1. O. Wolfbeis
"Fiber-optic chemical sensors and biosensors"
Anal. Chem., vol. 76, no. 12, pp. 3269-3284, 2004
Show Context

2. H. A. Rahman , S. W. Harun , M. Yasin , S. W. Phang , S. S. Damanhuria , H. Arof and H. Ahmad
"Tapered plastic multimode fiber sensor for salinity detection"
Sens. Actuators A, Phys., vol. 171, no. 2, pp. 219-222, 2011
Show Context

3. H. Golnabi , M. Bahar , M. Razani , M. Abrishami and A. Asadpour
"Design and operation of an evanescent optical fiber sensor"
Opt. Lasers Eng., vol. 45, no. 1, pp. 12-18, 2007
Show Context

4. S. Guo and S. Albin
"\'Transmission property and evanescent wave absorption of cladded multimode fiber tapers"
Opt. Exp., vol. 11, no. 3, pp. 215-223, 2003
Show Context

5. H. Rahman , S. Harun , M. Yasin and H. Ahmad
"Fiber-optic salinity sensor using fiber-optic displacement measurement with flat and concave mirror"
IEEE J. Sel. Topics Quantum Electron., vol. 18, no. 5, pp. 1529-1533, 2012
Quick Abstract | Show Context | Full Text: PDF

6. V. Kude and R. Khairnar
"Fabrication and numerical evaluation of the tapered single mode optical fiber: Detection of change in refractive index"
Indian J. Pure Appl. Phys., vol. 46, no. 1, pp. 23-29, 2008
Show Context

7. T. L. Yeo , T. Sun and K. T. V. Grattan
"Fibre optic sensor technologies for humidity and moisture measurement"
Sens. Actuators A, Phys., vol. 144, no. 2, pp. 280-295, 2008

8. S. Muto , O. Suzuki , T. Amano and M. Morisawa
"A plastic optical fibre sensor for real-time humidity monitoring"
Meas. Sci. Technol., vol. 14, no. 6, pp. 746-750, 2003

9. F. Arregui , Z. Ciaurriz , M. Oneca and I. Matias
"An experimental study about hydrogels for the fabrication of optical fiber humidity sensors"
Sens. Actuators B, Chem., vol. 96, no. 1â€"2, pp. 165-172, 2003

10. C. Bariain , I. Matias , F. Arregui and M. Lopez-Amo
"Optical fiber humidity sensor based on a tapered fiber coated with agarose gel"
Sens. Actuators B, Chem., vol. 69, no. 1â€"2, pp. 127-131, 2000
Show Context

11. J. Corres , J. Bravo and I. Matias
"Nonadiabatic tapered single-mode fiber coated with humidity sensitive nanofilms"
IEEE Photon. Technol. Lett., vol. 18, pp. 935-937, 2006
Quick Abstract | Show Context | Full Text: PDF

12. J. Corres , J. Bravo and I. Matias
"Sensitivity optimisation of tapered optical fiber humidity sensors by means of tuning the thickness of nanostructured sensitive coatings"
Sens. Actuators B, Chem., vol. 122, no. 2, pp. 442-449, 2007
Show Context

13. A. Gaston , I. Lozano , F. Perez , F. Auza and J. Sevilla
"Evanescentwave opticalfiber sensing (temperature, relative humidity and pH sensors)"
IEEE Sensors J., vol. 3, pp. 806-811, 2003
Quick Abstract | Show Context | Full Text: PDF

14. A. Gaston , F. Perez and J. Sevilla
"Optical fiber relative humidity sensor with polyvinyl alcohol film"
Appl. Opt., vol. 43, no. 21, pp. 4127-4132, 2004
Show Context

15. J. M. Corres , F. J. Arregui and I. R. Matias
"Design of humidity sensors based on tapered optical fibers"
J. Lightw. Technol., vol. 24, no. 11, pp. 4329-4336, 2006
Quick Abstract | Show Context | Full Text: PDF

16. K. S. Lim , S. W. Harun , S. S. Damanhuri , A. A. Jasim , C. K. Tio and H. A. Ahmad
"Current sensor based on microfiber knot resonator"
Sens. Actuators A, Phys., vol. 167, no. 1, pp. 60-62, 2011
Show Context

17. M. I. Zibaii , A. Kazemi , H. Latifi , M. K. Azar , S. M. Hosseini and M. H. Ghezelaiagh
"Measuring bacterial growth by refractive index tapered fiber optic biosensor"
J. Photochem. Photobiol. B, Biol., vol. 101, no. 3, pp. 313-320, 2010
Show Context

18. C. Beres , F. V. B. Nazare , N. C. C. Souza , M. A. L. Miguel and M. M. Werneck
"Tapered plastic multimode fiber-based biosensor"
Biosensors Bioelectron., vol. 30, no. 1, pp. 328-332, 2011
Show Context

AUTHORS

No Photo Available

Malathy Batumalay
Malathy Batumalay Photograph and biography not available at the time of publication.
More by this Author: IEEE Xplore

No Photo Available

Asiah Lokman
Asiah Lokman Photograph and biography not available at the time of publication.
More by this Author: IEEE Xplore

No Photo Available

Fauzan Ahmad
Fauzan Ahmad Photograph and biography not available at the time of publication.
More by this Author: IEEE Xplore

No Photo Available

Hamzah Arof
Hamzah Arof Photograph and biography not available at the time of publication.
More by this Author: IEEE Xplore

No Photo Available

Harith Ahmad
Harith Ahmad Photograph and biography not available at the time of publication.
More by this Author: IEEE Xplore

Sulaiman Wadi Harum

Sulaiman Wadi Harum Photograph and biography not available at the time of publication.

More by this Author: IEEE Xplore

CITED BY

None

KEYWORDS

INSPEC: Controlled Indexing

etching, fibre optic sensors, filled polymers, humidity measurement, humidity sensors, intensity modulation, polymer blends, refractive index

INSPEC: Non-Controlled Indexing

etching method, humidity sensitive cladding, humidity sensor, hydroxyethyl-cellulose/polyvinylidenefluoride composite, intensity modulation technique, polymer blend, refractive index, relative humidity measurement, size 0.45 nm, size 10 mm, tapered plastic optical fiber

Authors Keywords

Fiber optic sensor, humidity sensor, hydroxyethylcellulose/polyvinylidenefluoride (HEC/PVDF), relative humidity (RH), tapered plastic optical fiber

CORRECTIONS

None