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Bengtsson, Magnus; Wallstrom, S; Sjöholm, Mikael; Grönlund, Rasmus; Anderson, Benjamin; Larsson, A; Karlsson, S; Kröll, Stefan; Svanberg, Sune

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Fungus Covered Insulator Materials Studied with Laser-Induced Fluorescence and Principal Component Analysis

M. BENGTSSON,* S. WALLSTRÖM, M. SJÖHOLM, R. GRÖNLUND, B. ANDERSON, A. LARSSON, S. KARLSSON, S. KRÖLL, and S. SVANBERG

Department of Physics, Lund Institute of Technology, P.O. Box 118, SE-221 00, Lund, Sweden (M.B., M.S., R.G., B.A., S.K., S.S.); Department of Fiber and Polymer Technology, The Royal Institute of Technology, SE-100 44 Stockholm, Sweden (S.W., S.K.); Laser & Fiber Optics Centre, Department of Physics, University of Cape Coast, Cape Coast, Ghana (B.A.); and Weapons and Protection Division, FOI-Swedish Defense Research Agency, SE-147 25 Tumba, Sweden (A.L.)

A method combining laser-induced fluorescence and principal component analysis to detect and discriminate between algal and fungal growth on insulator materials has been studied. Eight fungal cultures and four insulator materials have been analyzed. Multivariate classifications were utilized to characterize the insulator material, and fungal growth could readily be distinguished from a clean surface. The results of the principal component analyses make it possible to distinguish between algae infected, fungi infected, and clean silicone rubber materials. The experiments were performed in the laboratory using a fiber-optic fluorosensor that consisted of a nitrogen laser and an optical multi-channel analyzer system.

Index Headings: **Fluorescence; Polymeric insulators; Fungal growth; Lidar; Remote sensing.**

INTRODUCTION

One of the basic needs of modern society is a reliable supply of electric energy. This need forces manufacturers of equipment for power generation, transmission, and distribution to develop better and more reliable components. One such component is the outdoor high-voltage insulator. These insulators have traditionally been made of porcelain or glass, but are now successively replaced by ones made of polymeric materials.[1] The new insulator materials make the insulators lighter, shatterproof, and easier to handle. However, their main advantage is their better electrical withstand performance, especially during foul weather conditions.[2] The better performance is due to the surface properties: a polymeric surface is hydrophobic (water-repellent), whereas water films are formed on a porcelain surface. Severe environmental conditions can, however, alter the surface properties of polymer surfaces, causing a temporary or permanent loss of hydrophobicity.

The presence of algae and fungi has for instance been found to disturb the hydrophobicity of the insulator surface, thereby decreasing the wet flashover withstand voltage.[3] Therefore, it is important to develop methods that can be used to identify polluted insulators. Today, there are no standardized or widely used techniques capable of detecting microbiological growth on the surfaces of silicone rubber insulators for field use. However, laser-induced fluorescence spectroscopy[4] is known to be a method that is both non-intrusive and capable of giving detailed information about the properties of the surface under study. Algal growth, for example, exhibits a characteristic fluorescence peak due to chlorophyll *a* at a wavelength of about 685 nm and can readily be detected at a surface illuminated by excitation light of, e.g., 355 nm wavelength generated by a frequency-tripled Nd:YAG laser.[5–7] However, fungal growth detection is a more demanding task. The fluorescence spectrum of silicone rubber covered by fungal growth has been shown to have a larger full width at half-maximum (FWHM) than the spectrum of a clean surface, but this effect is not always easy to determine without a more careful analysis of the spectrum.[8]

In this study a combination of laser-induced fluorescence (LIF) and principal component analysis (PCA)[9,10] is used in an attempt to develop an easily applicable method to detect fungal growth on silicone rubber. The method developed should be possible to use independently of the choice of silicone rubber and the type of fungal strain infecting the material.

EXPERIMENTAL TECHNIQUES

Materials. Silicone rubber with 20% SiO_2 filler and di(4-methyl benzoyl)peroxide added as a crosslinker was used as a base. For some samples the base was mixed with the flame retardants aluminum trihydrate (ATH) and zinc borate, as stated in Table I. Materials were kneaded in a 12 rpm Brabender internal mixer for 15 min prior to curing. The curing was performed in a Schwabentan Polystat press at a temperature of 180 °C and a pressure of 10 MPa. The resulting discs had a diameter of 200 mm and a thickness of 2 mm. Samples were post-cured for 4 h in a hot air oven at 200 °C before use.

Microorganisms. The microorganisms used were isolated from silicone rubber high voltage insulators collected from Sweden, Sri Lanka, and Tanzania.[11] The eight fungal cultures described in Table II were grown on malt extract agar for 28 days in room temperature before use.

Inoculation of Samples. Fungal spore suspensions were prepared by pouring 20 mL of the nutrient medium, described in Table III, on the agar surface of each of the cultures. The surfaces of the wetted cultures were scraped gently with a flame-sterilized platinum wire. The liquid was then slightly agitated and the suspensions were filtered through thin layers of glass wool into 100 mL glass-stoppered Erlenmeyer flasks prepared with 30 mL of nutrient medium and ten solid glass beads. The flasks were

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* Author to whom correspondence should be sent. E-mail: Magnus.Bengtsson@fysik.lth.se.

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TABLE I. Type and amount of flame retardant added in parts per hundred (pph) resin to the silicone rubber materials tested.

Material	Flame retardant
Base	No flame retardant added
Base + ATH	100 pph ATH
Base + ATH + zinc borate	90 pph ATH + 10 pph zinc borate
Base + zinc borate	10 pph zinc borate

shaken and the suspensions were sprayed onto the silicone rubber samples according to Table II. All samples were incubated for 45 days at 27 °C and 95% relative humidity before measurements were conducted. In these experiments fungal infected and clean samples could normally be differentiated by eye.

Instrumentation. The fiber-optic fluorosensor that has been used in the experiments consisted of a nitrogen laser, optics, a probe, and a detection system. The laser generated radiation in pulses (3 ns, ~15 Hz, ~1 μJ) at a wavelength of 337 nm. The laser light was guided via a telescope through a fused silica optical fiber (600 μm in diameter, numerical aperture of 0.22) to the sample under investigation. The tip of the fiber was placed about 1 mm above the sample. The laser-induced fluorescence was spatially emitted in all directions and a fraction of it was collected by the same fiber and guided back to an optical multi-channel analyzer system (OMA) consisting of a crossed Czerny–Turner spectrometer, a time-gated image intensifier, and a charge-coupled device (CCD) camera. The Peltier cooled detector had a CCD array of 1024 × 128 pixels, where the 128 vertical pixels were binned. The resolution of the OMA system, set by the 100 μm slit width, was 2.2 nm, and the spectrum could be recorded up to 805 nm. The gatewidth of the intensifier was about 100 ns and could efficiently suppress the ambient light by a factor of about 10^5. A compact housing contained all the electronics and optics, and a personal computer was used to control the fluorosensor and to store the fluorescence data. A detailed description of the fluorosensor is given in Ref. 12.

Analysis. Laser-induced fluorescence spectra, acquired by the nitrogen-laser-equipped OMA system, were accumulated from the silicone rubber materials and the fungal cultures in order to build one separate model (a PCA model) for each class of spectra (see Table II). Each spectrum was accumulated from 100 laser pulses and 20 spectra were used to build each of the models.

Prior to PCA, data were pre-processed by mean normalization and mean centering. The data set obtained was then simplified with a PCA that decomposes the data set into a structure part, containing the maximum amount of variation, and a noise part. The first principal component (PC) is the combination of variables that experiences the greatest amount of variation. The second PC describes the second greatest amount of variation orthogonal to the first PC and so on. An arbitrary spectrum can be reconstructed by adding a linear combination of the PCs to the average spectrum. The PCs are orthogonal and therefore uncorrelated. Higher order PCs correspond to small variances and can be seen as noise.

RESULTS AND DISCUSSION

The main purpose of this study was to evaluate a potential method that combines laser-induced fluorescence and principal component analysis to detect fungal growth on silicone rubber insulator materials. The purpose was also to decide what kind of a score plot, which is a scatter plot of the value of several principal components in the same plot, is best suited for the detection of fungal growth. A score plot can contain spectra of all materials and all biological growth but is then very difficult to utilize due to the formation of many groups of spectra that cannot be resolved. The PCs are dependent on the spectra analyzed, which makes it difficult to express too many groups of spectra by using only two PCs. A simplified score plot, which is based on only one variation, is easier to handle and capture by a PCA and can contain two well-separated groups of spectra. The fluorescence spectra of the four clean silicone rubber materials tested in this study are shown in Fig. 1. The different spectra are very similar in shape. However, a simplified score plot, based on the spectra of the insulator materials, still formed four different classes, as can be seen in Fig. 2. Ninety-five percent (95%) of the new clean material objects (spectra) have successfully been assigned to the existing classes by a soft independent modeling of class analogy (SIMCA) classification.[10,13] The classification is based on classical statistics, and the object-to-model distance and the distance of the object to the model center are both crucial to which classes the new objects belong. SIMCA catches the similarities between members of the same class and a new sample will not be rejected if it is similar enough.

Figure 3 shows typical fluorescence spectra, captured by the nitrogen-laser-equipped OMA system in the laboratory, of eight different fungal cultures grown on silicone rubber filled with ATH. Spectra obtained from the

TABLE II. Microorganisms used for inoculation of silicone rubber samples.

Country	Fungi	Base	Base + ATH	Base + ATH + zinc borate	Base + zinc borate
Sweden	*Epicoccum nigrum*		×		
	Microsphaeriopsis		×		
	Cladosporium cladosporioides	×	×	×	×
Sri Lanka	*Fusarium semitectum*		×		
	Polyscytalum fecundissimum		×		
	Stagonospora		×		
Tanzania	*Curvularia lunata*		×		
	Cladosporium tenuissimum		×		
Reference	Clean materials	×	×	×	×

TABLE III. Nutritive solution.

Substance	Amount
KH_2PO_4	0.7 g
K_2HPO_4	0.3 g
$MgSO_4\ 7H_2O$	0.5 g
$NaNO_3$	2.0 g
KCl	0.5 g
$FeSO_4\ 7H_2O$	0.01 g
Sucrose	30 g
Water	1 L

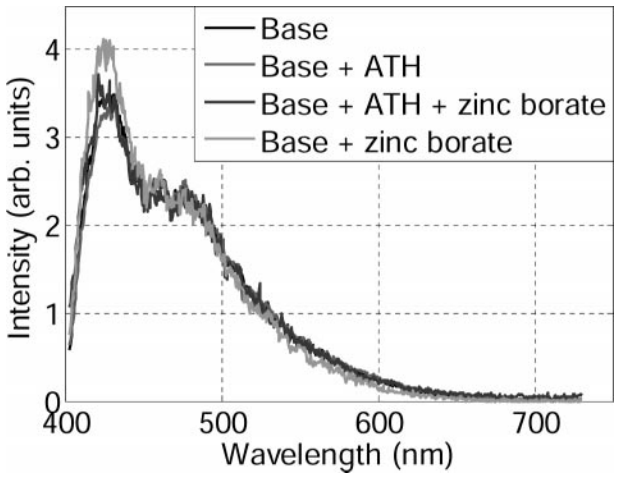

FIG. 1. Fluorescence spectra of the silicone rubber materials. The materials are presented in Table I.

fungus-covered samples have larger FWHM than the spectrum of the clean ATH-filled silicone rubber material and are located further to the left in the score plot (see Fig. 4). However, for some samples these effects are small and hard to detect in the spectra obtained. Results are easier to interpret from a simplified score plot of the sample set. As can be seen in Fig. 4 spectra of samples infected by fungal growth are spread out to the left in the score plot compared with the spectra of the clean material. The spread is due to the combination of fluorescence from the fungal growth and the material. A heavily contaminated sample is likely to end up further to the left in the score plot when compared with a cleaner sample. When results are displayed as a simplified score plot it is easy to differentiate a sample infected by fungal growth from a clean material. The different fungal cultures studied all followed the same trend in the simplified score plot, which is desirable for the development of a general inspection technique for composite insulators.

However, a useful method must be applicable to different materials as well as to different fungal cultures. In Fig. 5, fluorescence spectra of four different insulator materials are compared with spectra of samples of the same materials covered by fungal growth. Simplified score plots of the sample sets show that spectra of a fungus-covered material are spread out to the left in the score plots for the clean materials in all cases studied. The method seems to give the same general response regardless of the composition of the silicone rubber under study. A typical principal component is shown in Fig. 6. Spectra of all eight fungal cultures grown on the ATH-filled silicone rubber material and spectra of the clean ATH-filled silicone rubber, as shown in Fig. 4, have been analyzed. PC 1 describes the change between the spectra. By adding a negative contribution of PC 1 to the average spectrum, the resulting spectrum will have a larger FWHM.

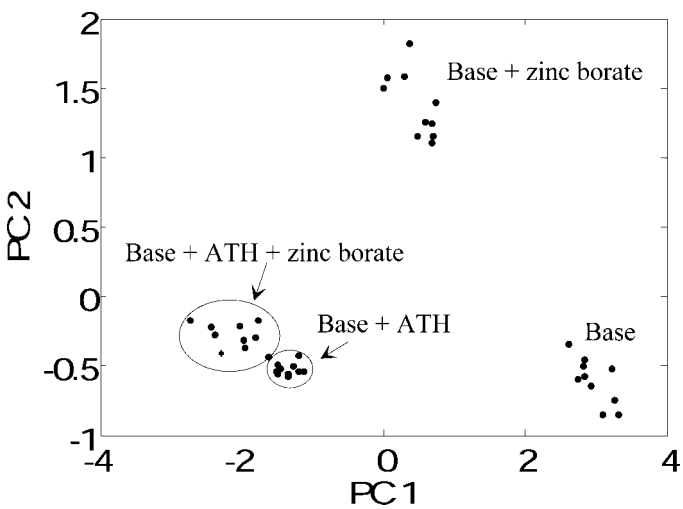

FIG. 2. Score plot of the four silicone rubber materials. For each of the four materials measurements were carried out at 10 different positions.

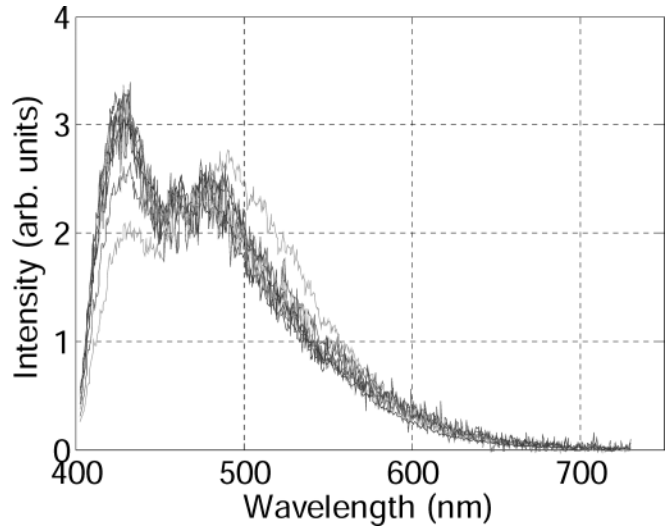

FIG. 3. Fluorescence spectra of all eight fungal cultures on the ATH-filled silicone rubber material. The fluorescence spectrum of the fungus culture *Stagonospora* shifts most to longer wavelengths.

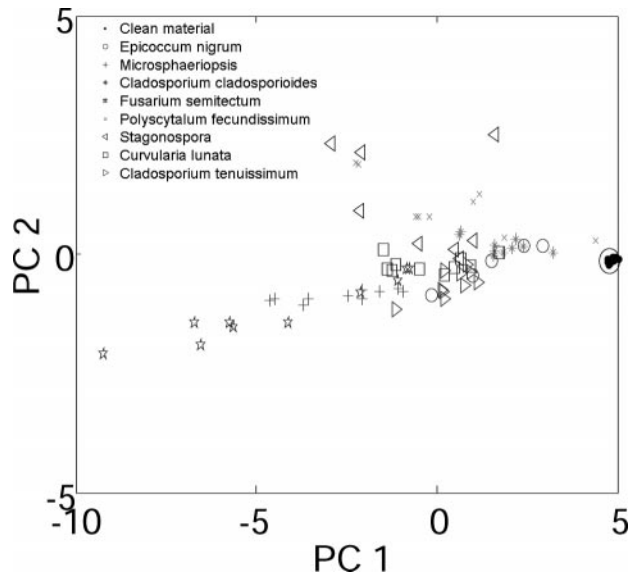

FIG. 4. The score plot contains a group of spectra of the clean ATH-filled silicone rubber material located within the circle. Spectra of all eight fungal cultures grown on the ATH-filled silicone rubber material are shown to the left. For each group measurements were carried out at 10 different positions. Outliers have been removed.

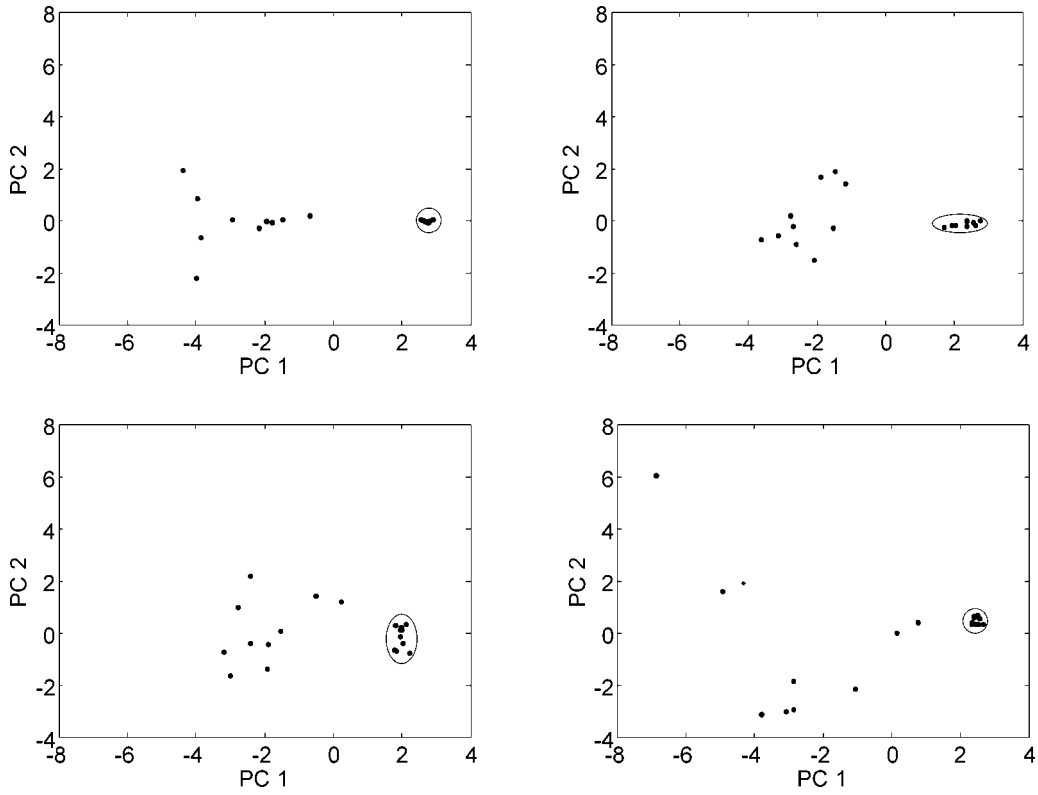

FIG. 5. Each score plot contains spectra of the clean material and the fungus culture *Cladosporium cladosporioides* grown on the material. Spectra of clean materials are located within the circles. Ten replicates were used in each group. (**Upper left**) Base material. (**Upper right**) Base + ATH. (**Lower left**) Base + ATH + zinc borate. (**Lower right**) Base + zinc borate.

The PCs for the spectra in Fig. 5 have been shown to be similar.

Laser-induced fluorescence in combination with principal component analysis is a promising method to detect fungal growth on silicone rubber materials. Contaminated silicone rubber samples analyzed with these methods give the same general response regardless of the composition of the silicone material and type of fungal contaminant under study. However, it is desirable to find the mechanism behind the responses observed. The signature of algae growth is a characteristic peak in the LIF spectrum due to chlorophyll *a* at a wavelength of about 685 nm. It would be an advantage if a similar relation between the laser-induced response of a fungal culture and some molecular component of it could be found. Nevertheless, it is possible to differentiate between algae, fungi, and

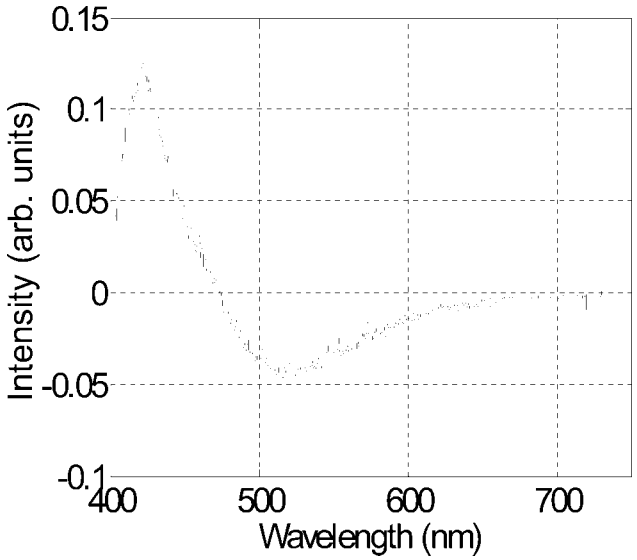

FIG. 6. The spectrum shows PC 1 as a function of the wavelength. A negative contribution of PC 1 explains why a fluorescence spectrum of fungal growth gives a larger FWHM.

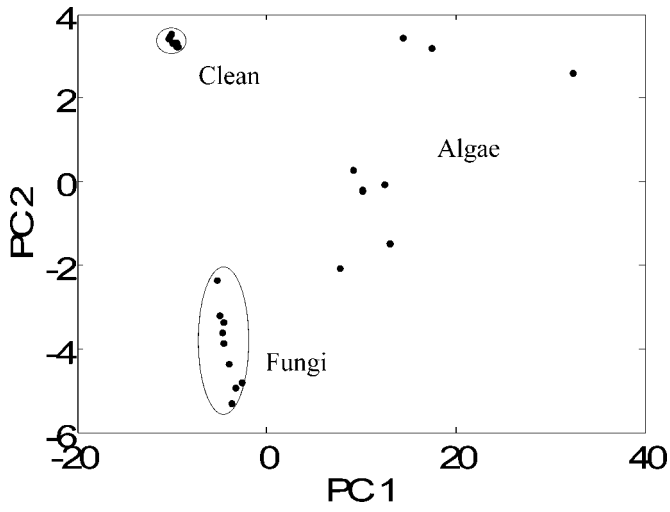

FIG. 7. Score plot of fungi, algae, and clean ATH-filled silicone rubber material. The spread of the algae fluorescence spectra is due to various heights of the algae peaks. The algae and fungi were grown on an ATH-filled silicone rubber material. For each of the three groups measurements were carried out at 9 different positions.

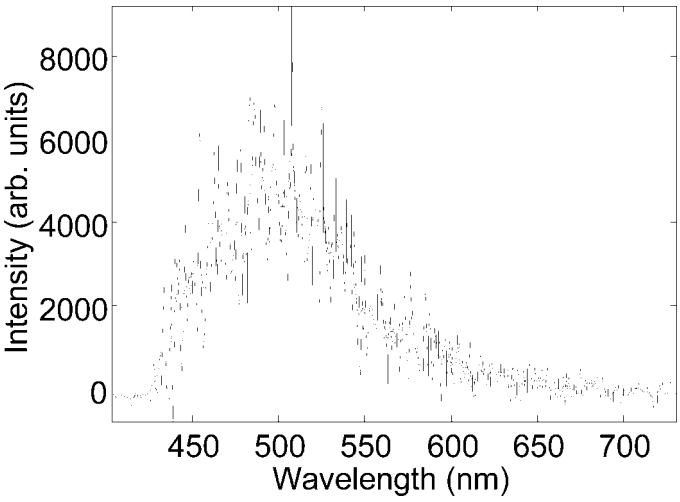

FIG. 8. The spectrum shows the fluorescence from *Cladosporium cladosporioides* only. The spectrum was accumulated from 150 laser pulses. Compared to clean materials, see Fig. 1, the fluoresence from the fungi is shifted to longer wavelengths.

clean surface by using a PCA (see Fig. 7). The fluorescence from pure fungal growth (see Fig. 8) is shifted to longer wavelengths and it is likely that the fungi signatures in combination with the fluorescence from clean materials can describe the larger FWHM from fungus covered materials. Future studies may include an investigation of aged insulator materials with a combination of laser-induced fluorescence and principal component analysis.

CONCLUSION

Laser-induced fluorescence in combination with principal component analysis proved to be useful as a tool to detect fungal growth on the surface of a silcone rubber material. The ability of the detection method to discriminate between clean and fungi infected samples was shown to be independent of the composition of the silicone rubber material as well as the type of fungal culture grown on the surfaces of the samples. This indicates that the method studied can be used as a general technique to inspect microbiological contaminations on high-voltage insulators made of silicone rubber. For field use fluorescence lidar techniques will be useful.[14] Then spectra of the type discussed in the present paper can be recorded remotely, and remote fluorescence imaging can also be performed.

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