PMMA Based Optical Fiber Bragg Grating for Measuring Moisture in Transformer Oil

W. Zhang and D. J. Webb

Abstract—**Water contamination can cause serious problems that compromise in transformer's safe operation and reduce its lifetime. Online monitoring of moisture concentration in transformer oil would permit the control of moisture buildup. This paper presents a direct optical measurement of moisture concentration in transformer oil using a poly(methyl methacrylate) (PMMA) based optical fiber Bragg grating. The refractive index and volume of PMMA based optical fiber vary with the moisture in the surrounding transformer oil, changing the reflecting wavelength of the grating. A sensitivity of POFBG wavelength change to moisture content of 29 pm/ppm is demonstrated in this work, indicating detectable water content better than 0.05ppm.**

Index Terms— **Fiber Bragg gratings, Polymer optical fiber, Moisture control, Equilibrium relative humidity.**

I. Introduction

TRANSMISSION and distribution transformers are some of the most critical and expensive assets in a power network. There are many reasons why high voltage transformers might fail, and one important possibility is the deterioration of the insulation. Water is a contaminant that has long been recognized as a major cause of trouble. If a small quantity of moisture is left in the dielectric, it acts to degrade the insulation and, via chemical action, produces more moisture. This naturally accelerates the deterioration of the dielectric and shortens the service-life of the transformer [1, 2]. Water in transformers can be found in different parts of the insulation system. It can accumulate in solid insulation, be dissolved in oil, or be found in the form of liquid water at the core or bottom of a transformer.

Because of its economic impact, moisture-in-oil measurement has attracted a lot of attention in recent years and various techniques have been proposed. A number of commercially available sensors have been tested in different conditions [3], which exploit the moisture dependent capacitance of transformer oil. However, they are basically electrical sensors which potentially are vulnerable to strong electromagnetic fields, and may decrease insulation breakdown strength. Another method for ppm determination of water content is the well-known Karl Fischer titration reaction. However, this method is not a real-time one and requires appropriate chemical instrumentation for its implementation. It is also prone to a high level of error and its results are often difficult to interpret. More important is that in most of methods, the moisture concentration in the oil is taken to be uniform, and this is clearly invalid. The moisture concentration will vary both with time and with transformer load. The moisture concentration of the oil can only be assumed to be uniform when the circulating speed is sufficiently high to produce a uniform temperature distribution, and this is a condition that has not been reached in transformers, even with forced oil cooling [4]. This means a distributive, real-time monitoring approach is required.

Fiber optic sensors have long been of interest to the electricity power industry [5]. Optical fiber's intrinsic EMI/ RFI immunity makes it ideal for harsh electrical environments. Optical fiber provides the necessary electrical isolation to drastically reduce the risks to people and equipment. An attractive feature is that an optical fiber sensor may be made compatible with any optical fiber network that is being exploited in the smart grid. Nowadays fiber Bragg grating (FBG) sensors inscribed in silica optical fiber have become an increasingly mature sensing technology. More recently, FBG sensors have been inscribed into PMMA based plastic optical fiber in both step-index and microstructured geometries. The physical and chemical properties of polymeric materials are rather different to silica and may offer advantages in certain situations [6].

A PMMA based optical fiber Bragg grating (POFBG) has an affinity for water which leads to a swelling of the fiber and an increase of refractive index. These features produce an increase in the Bragg wavelength of a FBG written in the fiber in response to rising water content in the fiber's environment [7], which is a potentially very useful property, and has possible applications in chemical processing, agriculture, food storage, paper manufacturing, semiconductor and pharmaceutical industries, where humidity is monitored and controlled to ensure product quality. This property is exploited in the detection of water in transformer oil in this work.

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II. Principle Of POFBG Sensing

Water dissolving in transformer oil from the surrounding air obeys Henry's law stating that the solubility of a gas in a liquid is directly proportional to the partial pressure of the gas above the liquid. In the absence of free water then, the amount of water dissolved in transformer oil depends on the relative humidity of the air. However, each oil has its specific water-saturation point beyond which excess water becomes either emulsified or free. The oil's saturation point is a function of many different factors such as the composition as well as the type of additives present. At a specified temperature and air pressure the water solubility is proportional to the environmental humidity. Data retrieved from [8] in the following figure shows the maximum water solubility at different temperature for three different transformer oils.

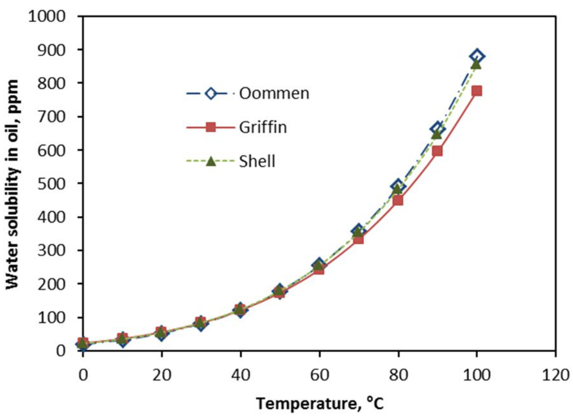

Fig. 1 Water solubility in transformer oil vs. temperature.

Water absorption in PMMA, as derived from the multimolecular theory of absorption, can be expressed as [9],

$$w = \frac{w_1 cx}{1-x}\left[\frac{1-(m+1)x^m + mx^{m+1}}{1+(c-1)x - cx^{m+1}}\right] \tag{1}$$

where w is the weight of absorbate per gram of adsorbent, w_1 the weight of absorbate per gram of absorbent when each absorption site is covered by one mole of absorbent, c and m are constants; $x = p_S/p_O$ where p_S is the equilibrium absorption pressure in the absorbate and p_O the saturation pressure over a free liquid surface of the absorbate. Here the absorbate is water and the absorbent PMMA and the ratio x represents the equilibrium relative humidity (ERH). For PMMA (Perspex), w_1 is 6.25, c=1, m=5. According to (1) water absorption in PMMA is a function of ERH and can be calculated.

Water absorption introduces changes in both volume and refractive index of PMMA. The volumetric change in PMMA can be estimated in terms of density change induced by water sorption [10]. The related fiber length change can be calculated using the following expression [7],

$$\Delta L = \frac{\Delta V}{3V_o} = \rho_w f w/300 \tag{2}$$

where f is the fraction of the water contributing to an increase in the PMMA volume and ρ_w the density of water.

The refractive index dependence of POF on water or humidity can be defined by the Lorentz-Lorenz relation [11]. According to the Lorentz-Lorenz relation, it is possible to derive the refractive index change caused by the change of volume V or polarizability α_P [12],

$$\Delta n = \frac{(n^2-1)(n^2+2)}{6n}\left(\frac{\Delta\alpha_p}{\alpha_p} - \frac{\Delta V}{V}\right) \tag{3}$$

The above equation can be used to calculate the refractive index dependence of humidity in PMMA based fiber provided that the change of volume or polarizability is known. For different material the changes of volume and polarizability are different, and are only determined through measurement. This relation between humidity and the refractive index of PMMA has been studied in detail in [13], which can be used to estimate the refractive index change of PMMA based optical fiber induced by humidity even though the fiber core is doped [14].

For a PMMA based polymer optical fiber Bragg grating (POFBG), its Bragg wavelength depends on the core effective refractive index n_{eff}, and the grating pitch Λ, both of which can be affected by the water content in the fiber. At a specified temperature the wavelength change of a POFBG against equilibrium relative humidity can be expressed as a function of absorbed water content in POFBG,

$$\lambda = 2n_{eff}(w)\Lambda(w) \tag{4}$$

III. Experiment And Results

The process of water contamination in transformer oil from the atmosphere obeys Henry's law. In equilibrium the amount of dissolved water depends on the relative humidity of the air around the oil. Oil close to an oil-water or oil-air interface will reach water equilibrium in a matter of minutes. Therefore the water content in a transformer oil sample can be varied by exposing oil to humid air. The amount of water in oil can be adjusted by changing the surrounding relative humidity. At equilibrium the water content in oil can be expressed by ERH.

An experimental arrangement was set up to control the dissolved water content in oil in this way and investigate the performance of a POFBG for water detection in oil. POFBGs were fabricated by attaching a ~10 cm length of POF to a single mode silica fiber down-lead using UV curable glue (Loctite 3525). The PMMA based POF (with a diameter of ~130 µm) contained a 5 mm long FBG, fabricated by illuminating from above a phase mask placed on top of the POF using 325nm UV light from a He-Cd laser [5].

For testing, the POFBG sensors were placed inside an environmental chamber (Sanyo Gallenkamp). They were illuminated via a fiber optic circulator with light from a broadband light source (Thorlab ASE730) and observed in reflection using an IBSEN I-MON 400 wavelength interrogation system.

Transformer oil was held in a beaker placed in the environmental chamber to be in contact with air that can be set to different temperatures and humidities. The POFBG was inserted into the oil and monitored under different relative humidity levels. The experimental arrangement is shown in Fig. 2.

The temperature of the environmental chamber was set at 24°C and the relative humidity was step changed from 40% through 55% and 70%, to 85% while the dwelling time at each humidity setting was 90 min. The measured response of POFBG is shown in Fig. 3.

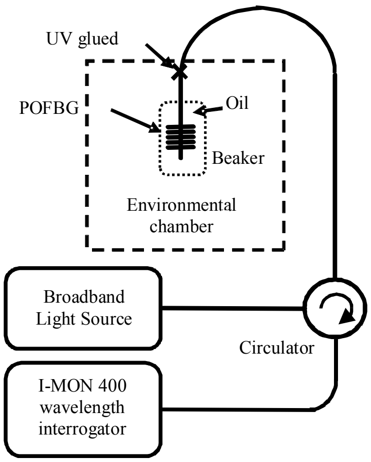

Fig. 2 Arrangement for measuring moisture in transformer oil

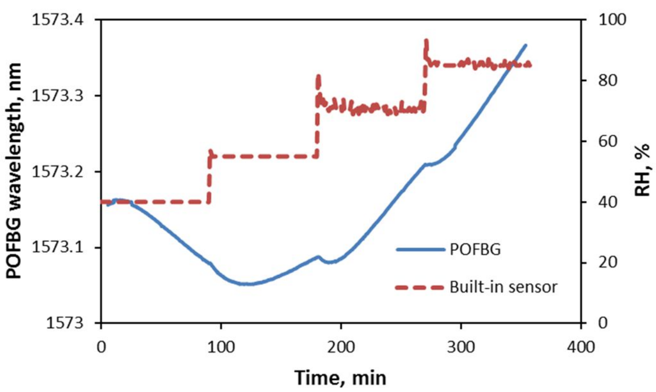

Fig. 3 POFBG response in oil at non-equilibrium.

It can be seen that the POFBG wavelength varies in response to relative humidity change, which alters the water content in the transformer oil. Room temperature was around 24°C, and the surrounding relative humidity between 50% and 60% before the experiment. Since first humidity level used in the experiment is less than the laboratory humidity the POFBG wavelength starts blue shifting after the relative humidity is set to 40% in the first step of the experiment. However, it is clear that POFBG response doesn't reach a stable value in the dwelling time of 90 minutes. There are two possible reasons for this slow response. One is that the influence of water on the fiber core is a diffusion process, taking time to complete [15]. The other is that it takes time for oil to reach water equilibrium with the surrounding environment. Fig. 4 shows a POFBG response over relative humidity step changing from 40%RH to 80%RH at 24°C. It indicates that for this POFBG sensor made of PMMA based optical fiber, the response time for a 10%RH step change is ~20 min. Hence we conclude that the time for oil to reach water equilibrium plays the more important role in the results shown in Fig. 3.

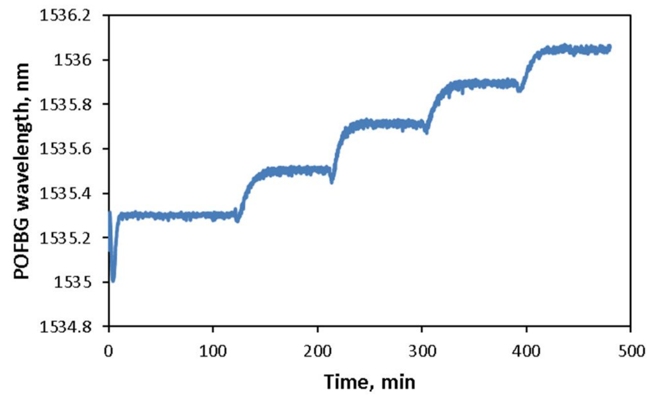

Fig. 4 POFBG response to relative humidity change.

To reach water equilibrium in oil one can either set a longer dwelling time for each humidity setting or accelerate the equilibrium process. A magnetic stirrer was used to stir the oil in the beaker so to accelerate the water equilibrium process in the oil. The wavelength response of the POFBG in transformer oil was monitored while the environmental conditions were set to the same as that in the previous experiment. The measured wavelength responses of the POFBG in oil are shown in Fig. 5. The two curves illustrate the response with a humidity dwelling time of 180 min without using the stirrer, and the response with a humidity dwelling time of 150 min with the oil being stirred.

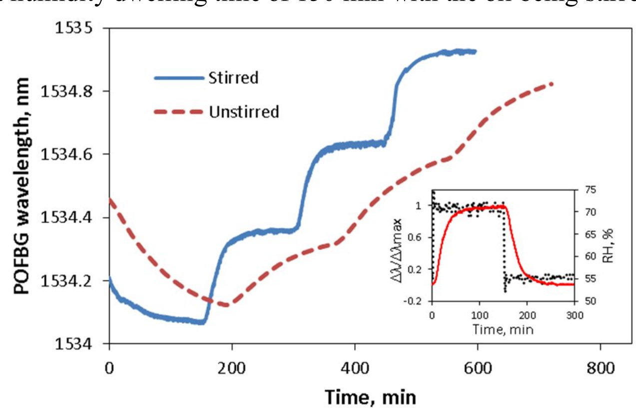

Fig. 5 POFBG responses in unstirred and stirred oil.

It should be pointed out that the starting wavelengths of the POFBG for stirred and unstirred oil are different. This is due to the different initial room temperature and relative humidity that may change, subject to the running of large equipment in the room. The POFBG response time is estimated as the time of the relative wavelength change ($\Delta\lambda/\Delta\lambda_{max}$) of the POFBG taken from its original value to 90% of maximum wavelength deviation induced by a step humidity change. In the stirred oil the POFBG shows a response time of ~55 min against a 15%RH step increase though this long response time mostly is attributed to the time required to achieve water equilibrium in the oil, rather than the time of the POFBG responding to moisture, which is typically much faster, as described earlier.

The inset in Fig. 5 shows the POFBG response in stirred oil over a full cycle of relative humidity change (55%RH to 70%RH to 55%RH). When the relative humidity has a 15%RH step decrease the POFBG shows a response time of ~57 min, slightly longer than that for 15%RH step increase. It looks in agreement with the results in [15] where the POFBG response time for water absorption is faster than that of water desorption. However, it should be remembered that the process here also incorporates the absorption/desorption of water into/from the oil, which dominates the time constant.

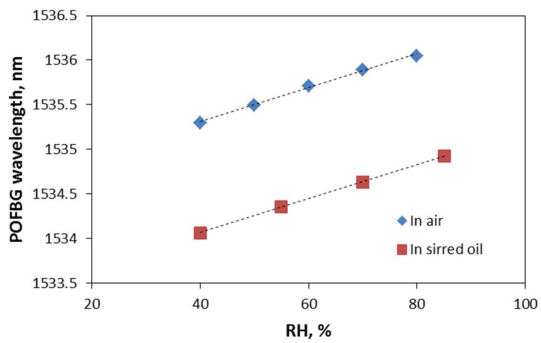

Fig. 6 The wavelength changes of the POFBG placed in air and in stirred oil against surrounding relative humidity.

The wavelength responses of the POFBG in air and in stirred oil are plotted against surrounding relative humidity, as shown in Fig. 6. The POFBG sensitivity over humidity change is ~19±3 pm/%RH for POFBG in air, and ~19±3 pm/%ERH in stirred oil. The uncertainty of ±3 pm/%RH is estimated mainly from the accuracy of setting the environmental conditions. From the retrieved data shown in Fig. 1 one can interpolate the water solubility in transformer oil at 24 °C, which is ~65 ppm (100%ERH) for Shell's transformer oil. Therefore the sensitivity of water content detection in transformer oil using the POFBG can be estimated as ~29 pm/ppm. The wavelength resolution for the I-MON wavelength interrogation system used in this work is ~1 pm. This suggests that the minimum detectable moisture concentration in oil is better than 0.05 ppm at constant temperature. This is a much better performance than any available water content detection instruments.

The POFBG sensor is sensitive to both relative humidity and temperature. Furthermore the sensitivity of the POFBG to relative humidity and temperature varies with both relative humidity and temperature [7]. Consequently, for real-world applications the sensor operation has to be calibrated against different surrounding conditions. A POFBG can operate in transformer oil with a silica optical fiber grating which is not sensitive to the relative humidity [16], to compensate the temperature cross sensitivity of the POFBG.

IV. Conclusion

We have proved theoretically and experimentally that a POFBG sensor can detect very tiny amounts of water in transformer oil. The experimental results demonstrated a much better moisture detection resolution than any other known technique. Due to its features of using optical fiber this technique provides the advantages of safe operation and online remote monitoring. Since the water equilibrium time closely depends on the volume and the geometry of the container, and oil circulating speed of the transformer, the moisture concentration in different part of transformer could be different. This requires multipoint, real time monitoring which optical fiber sensors can provide.

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