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Fabrication and characterization of multimode optical fiber sensor for chemical temperature monitoring using optical time domain reflectometer

Marwan Hafeedh Younus [a,b], Odai Falah Ameen [a,b], Norizah Redzuan [c], Norhayati Ahmad [c], Raja Kamarulzaman Raja Ibrahim [a,*]

[a] *Laser Center, Physics Department, Faculty of Science, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia*
[b] *Department of Physics, Faculty of Education, University of Mosul, 41002 Mosul, Iraq*
[c] *Department of Material, Manufacturing and Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia*

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Abstract

In this work, the optical fiber sensor system to measure the optical loss due to temperature variation of gasoline and toluene was papered. The optical fiber sensor was characterized using optical time domain reflectometer (OTDR). The sensor was a 50 cm multimode fiber with about 1–3 cm at its central region being partially unclad. The partial uncladding was carried out using chemical etching technique. The optical loss of sensor was measured when unclad part exposed to gasoline and toluene respectively at different temperature ranging from 25 °C to 60 °C. The optical loss of sensor increases in a step drop of OTDR trace as the temperature is increased. The rate of optical loss was estimated to be 0.01576 dB/°C and 0.02212 dB/°C for gasoline and toluene respectively.

Keywords: Optical fiber temperature sensor; Optical fiber chemical sensor; OTDR

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1. Introduction

Many material properties show strong temperature dependence, for examples density, electrical conductivity, refractive index, rigidity and diffusion [1,2]. Most of temperature dependence measurement tasks in industrial applications and the research can be carried out using conventional electric temperature sensors such as, thermocouples, junction temperature sensors, resistance temperature detectors or thermistors [2,3]. Despite the spreading of electrical sensors, their usage is impractical, if not entirely impossible in certain types of applications such as, chemical plants, landfills, chemical delivery pipelines, water ductworks, and similar applications. These types of sensors are

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[*] Corresponding author.

E-mail addresses: marwan.hafed@yahoo.com (M.H. Younus), rkamarulzaman@utm.my (R.K. Raja Ibrahim).

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susceptible to corrosive attacks and sensitive to various sources of error caused, for example, by electromagnetic interference [4,5]. Optical fiber sensors present clear advantages for operation in such extreme conditions. It can be used for remote measurements in environments which are hazardous or which suffer from the electromagnetic interference [6,7]. An optical fiber can act as the sensing element for a large variety of external parameters such as strain [8], temperature [9] and pressure [10], because it is able to survive to the harsh environmental constraints. Different classes of fiber-based sensors have been investigated, such as Fiber Bragg Gratings (FBGs) [11], Brillouin [12], Raman [13], Rayleigh scattering based techniques for distributed measurements [10], Mach-Zehnder interferometer sensors [14] and fiber surface plasmon resonance sensors [15]. The optical fiber sensors are categorized as either intensity or interferometric sensors. There are other optical techniques based on light scattering such as, radioactive losses [16], reflectance changes [17] and magneto-optic [18]. However the optical fiber sensor system must improve the performances for the temperature monitoring in the fields that depend on the temperature in their work such as generation of nuclear power reactors, spent-fuel pools and industries [2,19,20]. Moreover, other highly sensitive techniques were used for temperature monitoring such as, bandgap hybrid structures, polymer optical fibers, solid core photonic crystal fiber and hollow core photonic crystal fiber [21–25]. Of late, interest has turned to distributed fiber sensors, which enable the temperature to be monitored at many independent positions along fiber and thus to determine the thermal distribution and the location of hot spots. The first implementation of a distributed temperature sensor relied on optical time-domain reflectometry OTDR principle, invented by Barnoski and Jensen in 1976, which was the first method for distributed fiber measurements using backward Rayleigh scattering to determine the optical loss along fibers [26,27]. In such fibers, a localized temperature rise results in an increased scattering signal which may be detected and located by OTDR. Additionally, the OTDR enables to monitor the temperature profile along the length of a fiber continuously with a good response time and spatial resolution [28–31].

In this work, a multi-mode optical fiber (MMF) was used to demonstrate chemical temperature sensing. The sensor was fabricated by conventional chemical etching method using hydrofluoric acid (HF). An optical time domain reflectometer (OTDR) is used to determine the backscattering losses.

2. Theory of OTDR operation

In this study the (MW9070B) Optical Time Domain Reflectometer (OTDR) was used. It can be used to measure total loss, interval loss, splice loss and length of fiber. The main components of a conventional OTDR are laser diode (LD), detector avalanche photo diode (APD), an analog digital converter and a digital processor. The LD launch pulse light with low repetition into the fiber under test. Backscattered light is generated by Rayleigh scattering and Fresnel reflection in the fiber. The backscattered signals are introduced into the APD via a directional fiber coupler and averaged to improve the signal to noise ratio (SNR). Some of the light, thus scattered is guided by the fiber back to the launching end where it is detected by the receiver as shown in Fig. 1. The device operates at 1300 nm wavelengths with the pulse width range varied between 20 and 500 ns. The OTDR had the maximum dynamic range up to 50 dB and the average scan speed 150 s.

The resulting waveform in the OTDR device takes the shape of a decaying pulse since the forward-traveling pulse and that portion of the light which is scattered backwards are both attenuated by propagation along the fiber. Fig. 2 shows the whole trace of OTDR includes the splicing loss, connector reflection and Fresnel reflection. However, the scattered power $p(t)$ returning to the launching end after time t is given by equation (1) [31–33]

$$p_{(t)} = p_0 W \eta_{(z)} \exp - \left[\int_0^t \alpha_{(z)} V_g \right] \tag{1}$$

where p_o is the power launched into the fiber, W is the pulse width, V_g is the group velocity, $\alpha_{(z)}$ is the local attenuation coefficient and $\eta_{(z)}$ is the backscatter factor. Also, the distance z from the launching end is related to elapsed time t via equation (2) [31–33]

$$z = \frac{V_g t}{2} \tag{2}$$

3. Methods of fabrication MMF sensor and experimental setup

A 50 cm silica MMF with its core and cladding of diameters 50 and 125 μm respectively and RI of 1.41 was used. The gasoline and toluene with refractive indices 1.39 and 1.4961 respectively were used as samples to be detected by the sensor. A 1–3 cm length around the central region of the MMF was mechanically

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