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Cure real monitering sensor for UV curable thin epoxy film based on side-polished single mode fiber

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Abstract

A novel cure sensor based on the side-polished single mode fiber has been proposed and demonstrated. Two different UV curable epoxies were used to verify the feasibility of the side-polished single mode fiber as a high sensitivity cure sensor. The volume change of the epoxy by UV curing results in a corresponding change of the refractive index. The sensor can be used to monitor the curing process, the refractive index variation and the volume change of epoxy in real time during the UV curing process. In addition, small birefringence of the epoxy film can be detected using the sensor.

Key Words : UV curable sensor, side-polished fiber, epoxy film, refractive index

1. Introduction

It is important to monitor the curing process of composite epoxy or polymer for developing high performance product or providing optimized curing conditions. In particular, the curing time, refractive index variation and volume change of curable materials are key parameters in applications of optical packaging or optical waveguide. Various techniques, which are based on changes in dielectric[1], refractive index[2-4] and ultrasonic properties[5], have been reported for monitoring curing process of epoxy or polymer. In particular, in-line fiber-optic sensors offer many attractive benefits such as a small size, light weight and high resolution, as well as easiness in multiplexing and distributed sensing[6]. It is known that epoxy shrinks and its refractive index increases during curing. So changes in refractive index of bulky optical epoxy are used in the most of the fiber-optic cure sensors. It often needs to know the optical properties of thin epoxy film because it can be used as optical waveguide. In this case, the refractive index, film thickness and birefringence should be measured. To the our best knowledge, the previous reposted cure sensors[1-4], can not provide the information of the optical properties of thin film epoxy during the curing. The optical epoxy or polymer is often used as a material for thin film optical waveguide. The side-polished fiber half-block is suitable to coated the optical epoxy or polymer film on its polished surface. The polymer coated side-polished block has been applied as a thermo-optic tunable filter[8] and refractometers[9,10].

In this paper, we have investigated the applications of the side-polished fiber half-block as a sensor for monitoring the real-time UV curing process as well as evaluating change of the optical properties of optical epoxy induced by UV curing. The transmission of side-polished fiber depends on the refractive index of external medium placed on polished cladding surface. The feasibility of side-polished fiber as a sensor is based on the fact that the magnitude of loss strongly depends on the refractive index of the external medium[6]. If the side-polished optical fiber is covered with thin dielectric film, it exhibits strong wavelength selectivity. The methods, which are using intensity modulation or spectral response, for monitoring refractive index changes as well as birefringence during curing are presented. Furthermore, we will show that the changes in thickness of thin epoxy film coated on the side-polished fiber half block after curing can be detected.

2. Theoretical Consideration

Figure 1 shows the schematic structure of the side-polished single mode fiber covered with epoxy. Depending on the thickness of the epoxy film, the device

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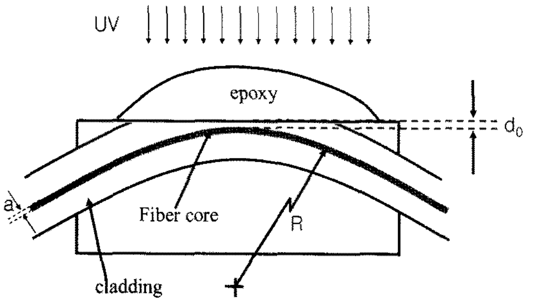

Fig. 1. The sensor structure using side-polished fiber covered with an epoxy layer.

behaves either a simple attenuator or a filter. At first, It is assumed that the epoxy film thickness is semi infinite. In this case the leaky loss occurs at the side-polished region by evanescent wave coupling if the refractive index of epoxy is higher than that of fiber core. The total attenuation in the device is a function of many structural parameters[6]. The fiber core radius, bending radius, and minimal remaining cladding thickness are denoted as a, R, and d_0 respectively, as shown in Fig. 1, while n_{co}, n_{cl}, and n_{ex} refer to the refractive index of the fiber core, fiber cladding, and external medium respectively.

The attenuation in the side-polished fiber covered with high index epoxy can be derived through the integration of the attenuation coefficient with respect to z[7].

$$Transmission[dB] = 10\cdot(log_{10}e)\cdot\sqrt{\pi Ra}\frac{4\beta_0}{n_{cl}^2 k_0^2}$$

$$\cdot\left[\frac{u}{aVK_1^2(w)}\right]^2\cdot\frac{V_{ep}^2-w^2}{V_{ep}^2}\int_0^1\frac{\sqrt{1-\xi^2}}{[\sqrt{(V_{ex}^2-w^2)\xi^2+w^2}]^{1/4}}$$

$$\exp\left[-2\frac{(d_0+a)}{a}\sqrt{(V_{ex}^2-w^2)\xi^2+w^2}\right]d\xi \qquad (1)$$

Where K_1, k_0, β_0, u, w, V are modified Bessel functions of the second kind of the first order, and are the free-space wave number, propagation constant of the fiber before polishing, normalized transverse propagation constant in the core and cladding of the single mode fiber, and fiber V number respectively. V_{ex} is the V number in the external medium placed on polished cladding surface, expressed as $V_{ex}=k_0 a\sqrt{n_{ex}^2-n_{cl}^2}$. In our calculation, the n_{cl}, n_{co} , a and d_0 are assumed to be 1.444, 1.448, and 4.0 μm respectively. The typical transmission of the side-polished single mode fiber as a function of refractive index of external medium is shown in Fig. 2.

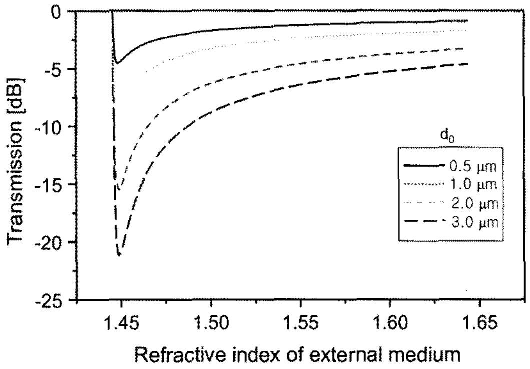

Fig. 2. The calculated transmission of the side-polished fiber as a function of refractive index of epoxy(n_{ex}) for various remaining cladding thickness(d_0).

Meanwhile, the epoxy film thickness is optically finite and uniform. The high index dielectric film plays a role of multimode planar waveguide (PWG). In this case, the behavior of the device can be explained by regarding it as an asymmetric directional coupler, so called fiber-to-PWG coupler[9,10]. Optical resonant power coupling from a fiber to a multimode PWG occurs when the effective refractive index of the highest PWG mode is close to the effective refractive index of the a fiber mode. The resonant couplings between fiber and PWG are periodically repeated with respect to the changes in film thickness(t), refractive index of film as well as wavelength[11,12].

Here, a simple expression for the thickness of PWG(t) by using two adjacent resonance wavelengths of the device can be obtained[12]. Let us define λ_{m+1} as resonance wavelength of m+1 *th* mode order of PWG and $\Delta\lambda$ denotes λ_m-λ_{m+1}.

$$t=\frac{\lambda_{m+1}\lambda_m}{2\pi\Delta\lambda(n_{ex}^2-n_{ef}^2)^{1/2}} \qquad (2)$$

Once the refractive index of epoxy film is known, the thickness of the film can be obtained by measuring the two resonance wavelengths.

3. Experiments and Analysis

The side-polished half blocks using conventional single mode fiber (Corning SM 28) for optical communications were fabricated. The curvature was 250 mm. It

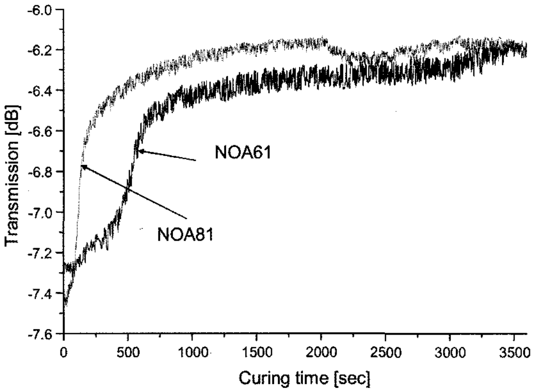

Fig. 3. The measured transmission of side-polished fiber covered with bulky epoxy during UV curing.

is assumed that refractive index of fiber core and cladding were 1.4485, 1.4440 respectively at 1550 nm wavelength. Core radius was assumed to be 4.0 μm. Two kinds of UV curing epoxy (Norland NOA 81 and NOA61) were employed in experiments. The products catalog notes that although the NOA 81 cures 3 times faster than the NOA61, the refractive indices of the two epoxies are the same when the curing process is completed. A mercury lamp with 5 mW/cm^2 was adopted as UV source. At first, we have measured the transmission changes of side-polished fiber covered with bulky epoxy during the UV curing process at room temperature (~25 °C). A 1550 nm LD was adopted as an optical source and the transmitted optical power was measured. The transmission loss of the side-polished fiber decreased with increasing time during the UV curing. It implies that the refractive index of the UV cure epoxy increases monotonically until the curing is completed. The experimental results show that the NOA81 has shorter curing time than NOA61 and the refractive indices of the two epoxy after curing are almost equal. It implies that device is suitable for monitoring curing process or for sensing the time when the cure is completed. The obtained refractive index of two epoxy around 1550 nm wavelength using equation(1) before and after curing are 1.5073 and 1.5428 respectively. Here, the effective index of fundamental fiber mode is set to 1.4456. In order to prove the validity of our method and to evaluate the usefulness, Another method using commercialized prism coupler to measured the refractive index of the epoxy was employed. The refractive index of NOA 81 epoxy at 1550 nm wavelength

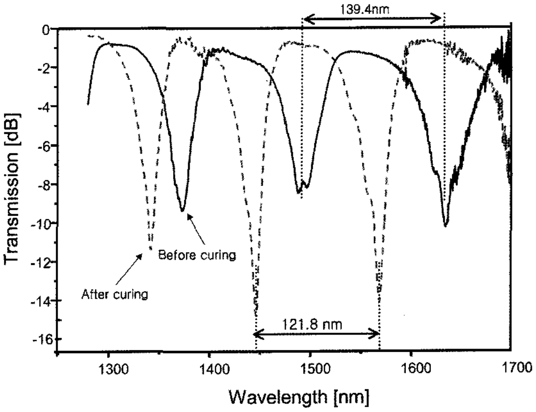

Fig. 4. The measured wavelength responses of side-polished fiber covered with epoxy film before and after curing.

before and after curing were found to be 1.5119 and 1.5490 respectively. The measured refractive index change during UV curing by the proposed method and by the prism coupling method were found to be 0.0355 and 0.0371 respectively. It is worth to note that refractive index spreads by the two different methods mentioned above after curing are almost equal to each other.

Finally, the thickness changes of UV cure epoxy after curing was measured. The epoxy was spin coated on the side-polished block. The wavelength responses of the sensor before and after the UV curing were measured using a spectrum analyzer and the experimental results are shown in Fig. 4. In order to completely cure the epoxy film coated on a side-polished block, the sample was exposed to mercury ramp with 5 mW/cm^2 optical power for two hours. In this case, both refractive index and thickness of the coated epoxy film changes during UV curing. Since we have know the refractive index of the epoxy before and after curing, the thickness of epoxy film before and after curing can be estimated using the eq.(2). The estimated thicknesses of film before and after curing were found to be 20.5 μm and 17.3 μm respectively. 15.6 % thickness variation induced UV curing was observed. In addition, it was found that the thin epoxy film after curing exhibited small a birefringence about 2×10^{-4}~3×10^{-4}. The birefringence of the epoxy film can be measured using the difference between two wavelength response of TE (transverse electric) polarization and TM (transverse magnetic) polarization. It is guessed that the birefringence of thin epoxy film is originated from the stress at epoxy-fiber cladding boundary. Since the sensor has in-line structure remote sensing and distribute sensing is possible. Real time curing process and curing complete time as well as change of refractive index and volume were induced by UV curing experimentally demonstrated.

4. Conclusion

In this paper, he applications of the side-polished single-mode fiber as a fiber-optic cure real monitering sensor and a tool to evaluate the change of optical properties of thin epoxy film induced by UV curing were reported. Two kinds of epoxy film were tested and the experimental result provided ample information about the curing properties including the curing time, the relative curing speed and the variation in the refractive index. The sensor showed about 1 dB variation in optical power due to 0.0355 change of refractive index during the UV curing. In addition, it is shown that the sensor can be used to the monitor the thickness variation of the thin epoxy film as well as the birefringence induced by UV curing._The sensor is expected to be used widely for cure monitoring of various epoxy and polymer materials because real time, in-situ, remote, distributed sensing is possible.

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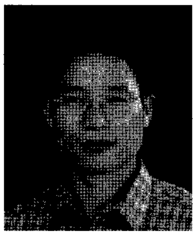

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