Research of Cable Identification Method Based on Single Fiber

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Abstract: Optical cable identification plays a very important role in cable maintenance and fault detection. In this paper, a new cable identification method based on optical fiber end reflection is proposed. Based on the theory of optical fiber sensor and phase modulation technology, single fiber optical cable identification is effectively achieved. System composition of this method is introduced in this paper. According to light interference principle, the expression of phase change when signal acts on fiber sensor is deduced; the relationship between redundant optical fiber and the system output signal is analyzed. The reasonable redundant fiber length is obtained by Matlab simulation, and the feasibility of the method is verified by experiment. Compared with other cable identification method, experimental results show that the single fiber optical cable identification has greatly improved in detection sensitivity and low maintenance time and costs.

1 INTRODUCTION

With the rapid development of optical fiber communication technology, it has become an important platform of much information, such as voice, data and images (Tan et al., 2006). As a basic transmission carrier of optical communication network, the optical cable has almost covered the major national backbone network. The portion of the cable label begins to blur, even to drop off with the time going on (Huang et al., 2007). So when optical cable has fault, it is a difficult work to identify the target cable quickly and easily (Yao and Zhang, 2008; Leonowicz et al., 2006). Based on optical fiber end face reflection, this paper proposed a new cable single fiber identification method according to the characteristics of the optical signal interference. This method achieves cable single fiber identification with fast response and has the same accuracy in the entire measuring range.

There are mainly three kinds of cable identification methods at present, including artificial pulling, optical power test, and dual fiber optic cable identification. Artificial pulling method is pulling the cable directly to identify the fiber optical cable along the damage locations by the maintenance workers. This method is very clumsy and consumes long time. Optical power test method is receiving end of the fiber optical power changes by real-time monitoring to achieve the object of identifying cable. This method is not accurate positioning and low accuracy. Dual fiber optic cable identification method (Sun and Chen, 2011) has high detection accuracy, but this method requires the double fiber loop, which cannot identify the only one dark fiber of the cable.

In this paper, a new cable identification method is proposed based on single fiber. This method will not damage to the cables, and high detection sensitivity, greatly reduce the fiber optic network management, repair and maintenance time and costs. Users can easily find the object cable by knocking the optical cable.

2 SYSTEM COMPONENTS OF CABLE SINGLE FIBER IDENTIFICATION

As is shown in Figure 1, the principle of single fiber identification system is light emitting from the light source via the coupler 1 divided into two paths. The first light reaches to coupler 2 directly, and then reaches reflection face via the sensor fiber, after reflection, reaches coupler 1 all the way through sensor fiber, coupler 2, and redundant fiber. The

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other light reaches coupler 1 directly without passing through redundant fiber. The second light reaches coupler 2 by passing through redundant fiber, and after being reflected by end face, is also divided into two paths of light, so the system has four optical paths:

Path 1: （a—b—c—b—d）;
Path 2: （d—b—c—b—a）;
Path 3: （a—b—c—b—a）;
Path 4: （d—b—c—b—d）;

The optical path difference between paths 1 and 2 is zero. These two lights will intervene after encounter in coupler1. Path 3 and path 4 does not satisfy the condition of zero optical path difference, so the interference does not occur.

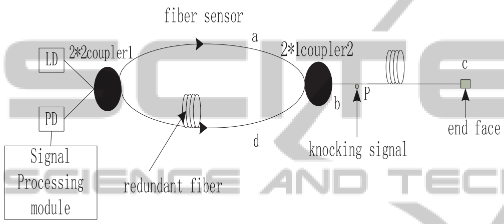

Figure 1: Single fiber cable identification system.

Therefore, when the external signal is acting on the fiber sensor, it will lead to changes of the phase shift of paths 1 and 2, produce a phase difference. The output expressions are,

$$E_1 = E_{10}\exp\{j[\omega_c t+\varphi_1(t)+\phi_1]\} \quad (1)$$

$$E_2 = E_{20}\exp\{j[\omega_c t+\varphi_2(t)+\phi_2]\} \quad (2)$$

Where, $E_{10}=E_{20}$ is the electric field amplitudes, ω_c is optical carrier frequency, ϕ_1 and ϕ_2 are the initial phase, (the initial phase of 2×2 coupler's output) [6-7], $\varphi_1(t)$ and $\varphi_2(t)$ are phase changes after two lights being modulated by knocking signal. The output expression of the total light intensity reaching the photoelectric detector is,

$$I = (E_1+E_2)(E_1+E_2)^* + E_3E_3^* + E_4E_4^* \quad (3)$$

Where E_3, E_4 are electric field amplitudes of path 3 and path 4.

According to equation (1)-(3), it can be deduced as,

$$\begin{aligned} I &= 4E_{10}^{\ 2} + 2\,\mathrm{Re}(E_1E_2^*) \\ &= 4E_{10}^{\ 2} - 2E_{10}^{\ 2}\cos[\varphi_1(t)-\varphi_2(t)] \end{aligned} \quad (4)$$

Therefore, when the external signal is acting on the fiber sensor, the optical phase difference change causes the interference fringes change. The external signal can be demodulated through the signal processing module, and enable to identify the target cable.

3 OPTICAL CABLE IDENTIFICATION PRESSURE AND PHASE ANALYSIS COPYRIGHT FORM

Figure 2 shows a fiber sensor expand schematic. Assuming that the optical fiber length is L, knocking signal is acting on the fiber sensor, its length is L_s. The expression of external signal for the fiber sensor is $p = p_0\sin(\omega_s t)$. p_0 is external signal amplitude, ω_s is external signal angular frequency.

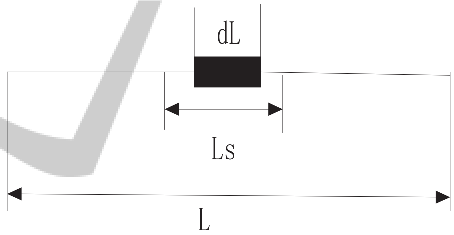

Figure 2: Fiber sensor expand schematic.

When knocking signal is acting on the fiber sensor, the phase change on any length l optical fiber is,

$$\begin{aligned} \Delta\phi &= \Delta\phi_\varepsilon + \Delta\phi_s \\ &= \beta_0 l\left(\frac{\Delta l}{l}\right) + l\left(\frac{\partial\beta}{\partial n}\right)\Delta n + l\left(\frac{\partial\beta}{\partial a}\right)\Delta a \end{aligned} \quad (5)$$

Where β_0 is light waves in optical fiber transmission constant, n is fiber refractive coefficient, l is light waves that spread of optical fiber length, $\beta_0 l\left(\frac{\Delta l}{l}\right)$ is the phase influence of tiny changes caused by strain. According to the theory of elastic mechanic (Wang et al., 2007), it can be deduced as,

$$\Delta\phi_\varepsilon = \beta_0\Delta l = \beta_0\varepsilon_z l \quad (6)$$

Where, $l\left(\frac{\partial\beta}{\partial n}\right)\Delta n$ is the influence on phase of β_0 changes, which is caused by optical fiber refractive coefficient changes through photo elastic effect, $l\left(\frac{\partial\beta}{\partial a}\right)\Delta a$ is waveguide effect, phase change caused by the change of the fiber core， which can be negligible.

According to the theory of elastic mechanic [9-10], it can be obtained,

$$\Delta\phi_s = -\delta\beta * p * dl = -\delta\beta * p_0 \sin(\omega_s t) * dl \tag{7}$$

$$\delta\beta = \frac{1}{2}kn^3(1-2\mu)(p_{11}+2p_{12})/E \tag{8}$$

Where, k is the number of waves of light in a vacuum, μ is the Poisson constant of the fiber，p_{11} and p_{12} are elastic tensor component, E is the elastic modulus of the optical fiber.

According to equation (5) – (8) it can be deduced as,

$$\Delta\phi = \beta_0\varepsilon_z l - \delta\beta * p_0 \sin(\omega_s t) * dl \tag{9}$$

Figure 3 plotted the light path of the single fiber cable identification system. The spread of the light will be modulated and cause phase change when knocking signal is acting on the coherence light of path 1 and 2.

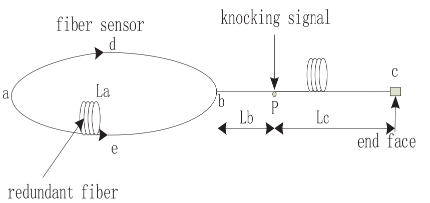

Figure 3: The light path of the single fiber cable identification system.

According to equation (9) it can be deduced as,

$$\varphi_1(t) = \int_0^L \beta_0 dl + \int_0^{L_s} \beta_0\varepsilon_z dl - \int_0^{L_s} \delta\beta * p_0 * \{\sin\omega_s(t-\tau_1) + \sin\omega_s(t-\tau_2)\}dl \tag{10}$$

Where $\tau_1 = \frac{n(l_a+l_b)}{c}$ is the transition time when light transits from a point to knocking point p by point d and point b.

$\tau_2 = \frac{n(l_a+l_b+2l_c)}{c}$ is the transition time when light transits from a point to end face and then reflected to the knocking point p through point d and point b.

$$\varphi_2(t) = \int_0^L \beta_0 dl + \int_0^{L_s} \beta_0\varepsilon_z dl - \int_0^{L_s} \delta\beta * p_0 * \{\sin\omega_s(t-\tau_3) + \sin\omega_s(t-\tau_4)\}dl \tag{11}$$

$\tau_3 = \frac{n(l_b+l_a+l_d)}{c}$ is the transition time when light transits from point a to knocking point p by point e and point b.

$\tau_4 = \frac{n(l_b+l_a+2l_c+l_d)}{c}$ is the transition time when light transits from point a to end face and then reflected to the knocking point p through point e and point b.

According to equation (10) and (11), after two beams of coherent light modulate, the phase difference can be obtained,

$$\Delta\varphi(t) = \int_0^{L_s} \{\delta\beta * p_0 * \{[\sin\omega_s(t-\tau_1) + \sin\omega_s(t-\tau_2)] - [\sin\omega_s(t-\tau_3) + \sin\omega_s(t-\tau_4)]\}\}dl \tag{12}$$

According to equation (12), the following equation can be obtained,

$$\Delta\varphi(t) = 4\delta\phi \sin\omega_a\left(\frac{\tau_d}{2}\right)\cos(\omega_a\tau_a)\cos\omega_a\left(t-\frac{\tau_x}{2}\right) \tag{13}$$

$$\delta\phi = \frac{1}{2}kn^3(1-2\mu)(p_{11}+2p_{12})p_0 L_s / E \tag{14}$$

Combined equation (4) and (13), photoelectric detector output signal can be deduced as,

$$I = 4E_1^2 - 2E_1^2\cos[4\delta\phi\sin(\omega_a\frac{\tau_d}{2})\cos(\omega_a\tau_a)\cos\omega_a(t-\frac{\tau_x}{2})] \tag{15}$$

Where $\tau_d = [(\tau_3+\tau_4)-(\tau_1+\tau_2)]/2$ is the transition time, when light goes through the redundant optical fiber; $\tau_a = [(\tau_4-\tau_3)+(\tau_2-\tau_1)]/4$ is the transition time when light is reflected from knocking point p to reflection end face; $\tau_x = \tau_2 + \tau_3$ is the transition time when light goes from path 1 to path 4.

According to equation (15), it can be found that $\delta\phi\sin(\omega_a\frac{\tau_d}{2})$ will affect the sensor's optical signal-to-noise ratio. The system output signal is weak when it is small. Therefore, it is critical to choose the appropriate redundant optical fiber length to improve the optical signal-to-noise ratio of the system.

4 ANALYSIS LENGTH OF REDUNDANT FIBER

According to (15), the output light intensity of the system I changes with $\Delta\varphi(t)$ periodically. When $\Delta\varphi(t) = (2k+1)\pi \quad k = 0,1....N$, the output light intensity reaches to maximum value. As we all known that the frequency of knocking signal ranges from 1.4KHz to 2.6KHz and the length of the tested cable is in the kilometer magnitude, so $\cos(\omega_a\tau_a)\cos\omega_a(t-\frac{\tau_x}{2}) \approx 1$ where $\Delta\varphi(t)$ is determined by $\delta\phi\sin(\omega_a\frac{\tau_d}{2})$. In real knocking process, phase shift caused by knocking signal equals to approximately 8π (Liu et al., 2004), so it can be known that the relationship between the length of redundant fiber and the system output by simulation.

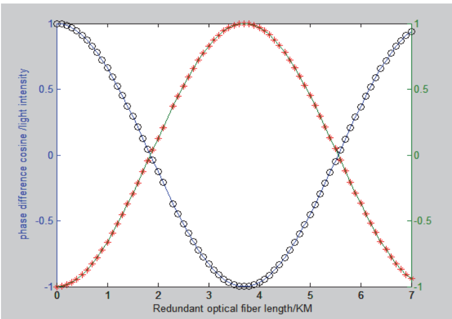

Figure 4: Phase difference cosine /light intensity values of different redundant fiber.

In Figure 4, it can be seen $\cos[\Delta\varphi(t)]$ (black curve) and light intensity I (red curve) changes periodically with the length variation of redundant fiber (Equation (4) shows an inverse relationship between these two variables). It can be found that the system output signal amplitude of different redundant fibers.

Based on the analysis results, the system light intensity output will reach to the maximum when the length of redundant fiber is in the range from 3.7 to 4.3km. Therefore, redundant fiber length can be selected within this range.

5 EXPERIMENTAL ANALYSIS

5.1 Simulation Test

Due to PC connectors reflection loss is the largest, it can be selected as the reflection end face. PC reflection loss is 18 dB, two coupler loss are 6 dB, 4km redundant fiber loss is measured as 0.8 dB, and optical fiber connection loss is 1.5 dB. So the loss of whole light path is,

$$p_{loss} = 18 + 2*3 + 0.8 + 0.3*5 = 26.3\text{dB} \tag{16}$$

In the experiment of cable single fiber identification, the maximum laser luminous power is 1 dBm, detector sensitivity is -46 dBm, and the fiber loss in the engineering is 0.25 dB/km. So the cable length can be identified in this system,

$$l = [-1-(-46)-24.8]/(2*0.25) = 40\text{km} \tag{17}$$

Figure 5 shows the simulated test platform.

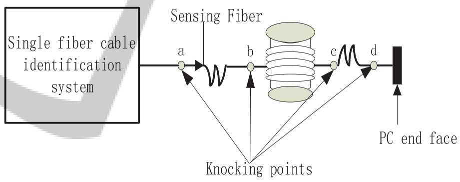

Figure 5: Simulated test platform.

In the experiment, select a, b, c, d four knocking points, and observe the output light intensity signal waves. Signal waveforms are plotted in figure 6 and figure 7.

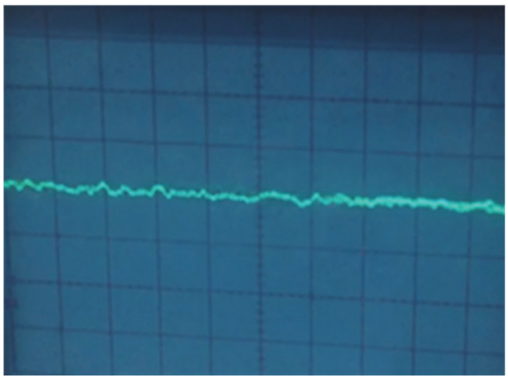

Figure 6: Background noise signal waveform.

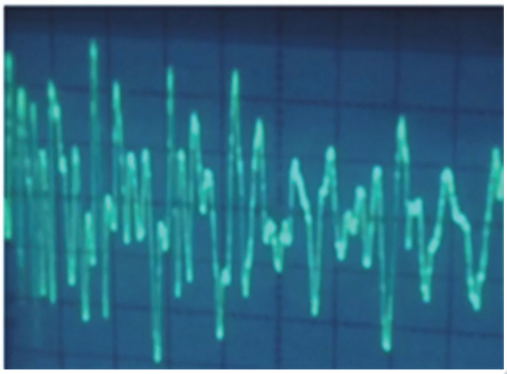

Figure 7: Knocking signal waveform.

As can be seen from figure 6 and figure 7, when knocking on one of a, b, c, d points, the signal amplitude is larger than the background noise signal obviously. Therefore the object cable can be identified through the detected knocking signals. The identified distance can reach to 40km, which can satisfy the practical requirements.

5.2 Field Test

The experiment was carried on the transmission cable of the China Unicom in Shandong; put the single fiber cable identification system on the local working room, and connect the dark fiber of the object cable. Disconnect the other end dark fiber of object cable with connector of equipment in remote working room so as to be convenient for the sensing signal reflection. The optical cable field test platform is shown in figure 8:

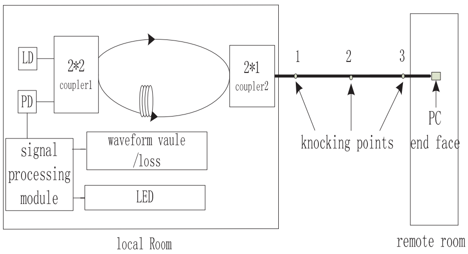

Figure 8： Field test platform.

We knock the near end 1, middle 2 and far end 3 in the transmission cable. Waveform value represents the voltage of PD detection. LED counts represent the receiving audio signal strength of system. The test results are shown in figure 9-12.

It can be measured that the length of the cable is 29 km by using OTDR. The cable loss is 0.25 km/dB according to the requirement of engineering, so the cable loss is 7.25 dB, the cable loss of the single fiber optic cable identification system is 7 dB, which is close to the theoretical value 7.25 dB, When knocking the near end, middle and far end of the object optical cable, waveform value is close to a maximum of PD detection 5V, and we can clearly hear hammering at the same time. When knocking on the neighbouring cable, we can't hear the hammering, because of the disturbance of the noise, so there is a small waveform value.

From test results, we can find that the single fiber optical cable identification system can effectively identify the object optical cable.

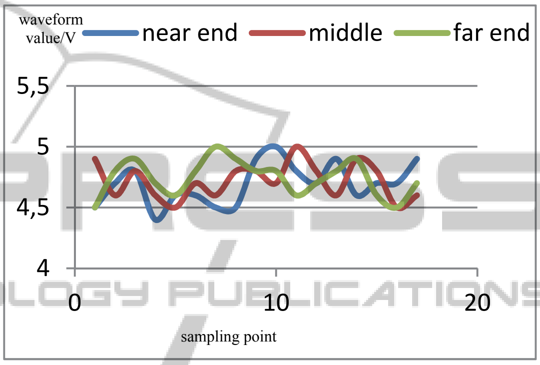

Figure 9: Waveform value when knocking the object optical cable.

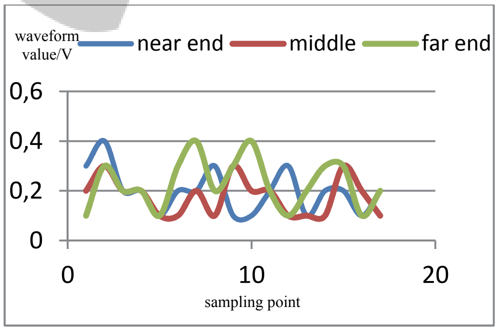

Figure 10: Waveform value when knocking the neighbouring optical cable.

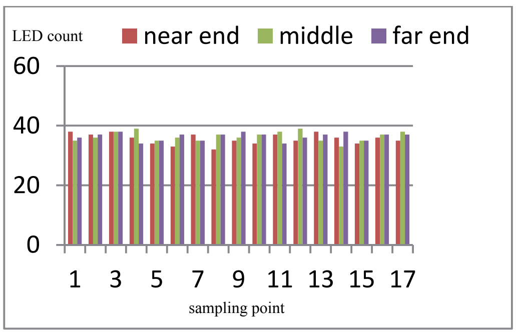

Figure 11: Audio signal strength when knocking the object optical cable.

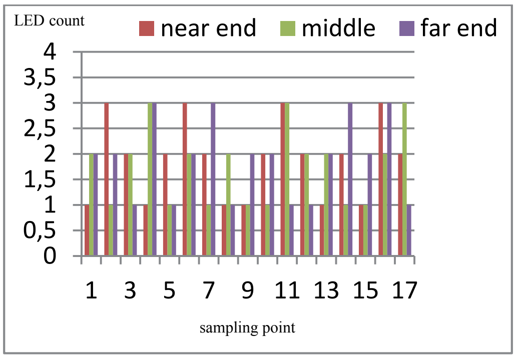

Figure 12: Audio signal strength when knocking the neighbouring optical cable.

6 CONCLUSION

This paper proposed the single fiber optical cable identification method. It has greatly improved compared with other methods in high detection sensitivity and low maintenance time and costs. Users can easily find the target cable by knocking the optical cable.

Based on the theory of light interference, this paper analyzed the system structure and basic principle of the method, derived the external signal and the phase change caused by the sensing optical fiber, got the proper redundant optical fiber length through Matlab simulation analysis, solved the key issues of single cable identification. Simulated test platform is set up in the laboratory; The loss of reflection face is measured; The maximum length of cable identification is calculated. Finally it versified the feasibility of this method by field test and data analysis.

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