Application of Golay codes to distributed optical fiber sensor for long-distance oil pipeline leakage and external damage detection

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A new distributed optical fiber sensor system for long-distance oil pipeline leakage and external damage detection is presented. A smart and sensitive optical fiber cable is buried beneath the soil running along the oil pipeline, which is sensitive to soakage of oil products and mechanical deformation and vibration caused by leaking, tampering, and mechanical impacting. The region of additional attenuation can be located based on the optical time domain reflectometry (OTDR), and the types of external disturbances can be identified according to the characteristics of transmitted optical power. The Golay codes are utilized to improve the range-resolution performance of the OTDR sub-system and offer a method to characterize the transmitted optical power in a wide range of frequency spectrum. Theoretic analysis and simulation experiment have shown that the application of Golay codes can overcome the shortcomings of the prototype based on the conventional single-pulse OTDR.

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Oil pipeline leakage can release huge amounts of hazardous chemicals and result in serious environmental pollution and damage to lives and property. It is important to monitor pipeline health, and to predict and locate leakage promptly. There have been many pipeline detection techniques developed over the years based on distributed optical fiber sensor (DOFS)[1−5]. But most of them focused all their attention on detecting oil leakage and have not been capable of detecting or classifying external damages to the pipeline. To overcome these problems, a sensitive optical fiber cable was proposed[6]. A sensing fiber coated with a thin skin is aligned together with and inside a small groove in a rubber wire, and then coupled mechanically by a soft steel wire coiled round them. The skin has periodical hardness along its length and has an additional function to induce additional bending-loss inside fiber under external force or pressure. The rubber wire can reversibly swell under oil influence and induce the bending losses in the fiber.

An optical fiber cable can be installed along an oil pipeline as a sensor to monitor pipeline conditions. When oil leakage happens, high-speed liquid streaming from the pipeline can impact continuously upon the ground, which will disturb the cable and result in the fiber in the cable to vibrate and bending-loss to occur. The tampering and mechanical impacting can also cause cable bending and the additional attenuation will occur inside fiber. When a small crack or corrosion happens, oil may ooze out of the pipeline, the seepage may be too small to be sensed directly by the fiber. The rubber wire has an ability to absorb oil and swell significantly in its physical dimensions. Through the action of periodic cabling geometry, the swelling can cause a mechanical deformation of fiber and induce bending-loss. The region of the additional attenuation can be detected and located based on the optical time domain reflectometry (OTDR); meanwhile, the types of external disturbances can be identified according to the characteristics of transmitted optical power received by an optical power meter. The architecture of the DOFS for long-distance oil pipeline leakage and external damage detection is illustrated in Fig. 1[7].

As shown in Fig. 1, an optical pulse is injected into and propagates along the sensing fiber, and the pulse is received by the transmitted optical power-meter on the other end of the fiber. Meanwhile, a fraction of light is backscattered and received by the backscattered optical power-meter. The OTDR sub-system correlates what it sees in backscattered light with an actual location on fiber. Therefore, the spatial variation of attenuation along the fiber can be derived from the backscattered light. But the backscattered light is very weak, typically 40 dB or more down from the launch power[8]. When the peak pulse power reaches its maximum practical value, a simple way of increasing the backscattered light is to make the probe pulse longer, but unfortunately it in turn degrades the response resolution of the measurement. Another way is to repeat measurements and average the resulting data of multiple probe pulses, which has been proved most useful but has a range-velocity limit. Once a pulse is injected into the fiber, all the backscattered light must have returned before the pulse repeats, otherwise it is impossible to separate the backscattered light of the former pulse at a distant point from the backscattered

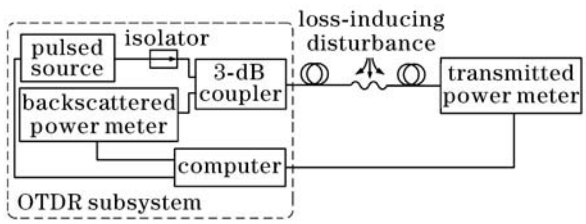

Fig. 1. Architecture of the DOFS.

light of the later pulse at a close point. The minimum interval T between the pulses is determined by

$$T = 2 \times \frac{Z}{C} \times n_1, \tag{1}$$

where Z is the length of fiber, C is the velocity of light, and n_1 is the refractive index of fiber core. Therefore, as the length Z increases, the time interval T must be increased, and the pulse rate must be reduced.

When the optical probe pulse is propagating along the sensing fiber, it is modulated in amplitude by the external disturbances. The optical pulse needs to repeat itself at intervals, which can be treated as the sampling signal of transmitted optical power. According to the sampling theorem, the pulse rate must be chosen to be at least twice the maximum frequency of the transmitted optical power. To monitor oil pipeline over 50 km, the length of the fiber must be more than 50 km. The minimum interval T approximates 0.0005 s and the maximum rate f of the pulse is 2000 Hz when n_1 is 1.5. But it is observed that the maximum frequency of the transmitted optical power is close to 5000 Hz[9], so there exists a conflict between the maximum rate of the sampling pulse and maximum frequency of the transmitted optical power. To overcome the conflict, the complementary code pair, known as Golay codes, is applied into the DOFS for long-distance oil pipeline leakage and external damage detection.

The Golay codes are a pair of complementary sequence codes and their autocorrelation functions have complementary sidelobes[10]. Assuming A, B to be a pair of L-element sequences of Golay codes, their autocorrelations are

$$\begin{cases} r_A(k) = \sum\limits_{n=0}^{L-1-k} A(n)A(n+k) \\ r_B(k) = \sum\limits_{n=0}^{L-1-k} B(n)B(n+k) \end{cases},$$

$$k \in [-(L-1),(L-1)]. \tag{2}$$

The sum of their autocorrelations, $r_A(k)$ and $r_B(k)$, is

$$r_A(k) + r_B(k) = 2L\delta_k, \tag{3}$$

where

$$\delta_k = \begin{cases} 1 & k = 0 \\ 0 & k \neq 0 \end{cases}. \tag{4}$$

The Golay codes, A and B, can be constructed by iterative procedures of appending, which generates a $2L$-element code pair from a L-element code pair[11]:

$$A^{(n+1)} = A^{(n)} \Big| B^{(n)}$$

$$B^{(n+1)} = A^{(n)} \Big| \overline{B^{(n)}}, \tag{5}$$

where $\overline{B^{(n)}}$ denotes the complement of $B^{(n)}$, obtained by swapping 1' s and $-1'$ s, and "|" denotes the concatenation of sequences. Therefore the length of Golay codes is power of 2. For instance, when $A^{(0)} = 1$ and $B^{(0)} = 1$, the waveforms of 64-bit Golay codes, A and B, are illustrated in Fig. 2.

The autocorrelations of A and B and their sum are illustrated in Fig. 3.

The Golay codes have been applied to offer improved range-resolution performance of the OTDR, called correlation OTDR[11]. Then the correlation OTDR had been improved by injecting a code set of three probe signals[12]. The three probe signals are an all-ones codeword and a pair of unipolar Golay codewords. The all-ones codeword is a L-element sequence of bit 1. The Golay codes are bipolar and cannot be injected directly into the fiber system. To overcome this physical constraint, the Golay codes are transformed into unipolar form by adding a bias which is equal to half of the available peak power.

In the OTDR sub-system of the DOFS, the bipolar Golay codewords, $A^{(n)}$ and $B^{(n)}$, are transformed into unipolar form by a bias, which maps the bit 1 to the maximum practical value of injected optical power and bit -1 to the half of the maximum. For example, P_A and P_B, showed as follows, are the unipolar forms of A and B, a pair of 64-bit complementary sequences of Golay codes.

$$\begin{cases} P_A = 0.75 \times \hat{1} + 0.25 \times A \\ P_B = 0.75 \times \hat{1} + 0.25 \times B \end{cases}, \tag{6}$$

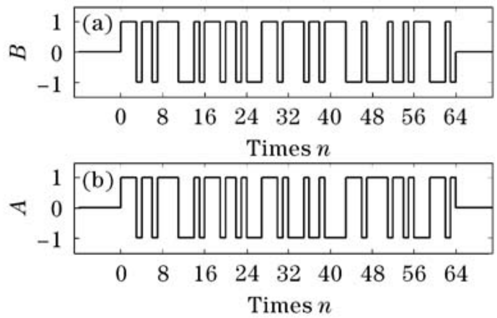

Fig. 2. Complementary Golay codes. (a) and (b) are individual waveforms of each code of a 64-bit Golay code pair.

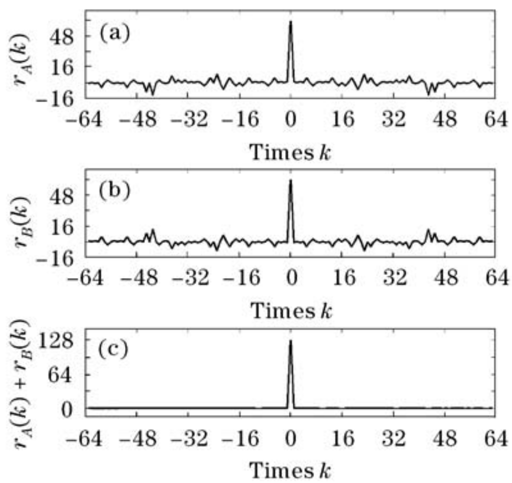

Fig. 3. Autocorrelation functions of the 64-bit Golay code pair, A, B, and their sum. (a) and (b) are the individual autocorrelations of each codes, and (c) is the sum of the autocorrelations. The sum is exactly zero except at the origin.

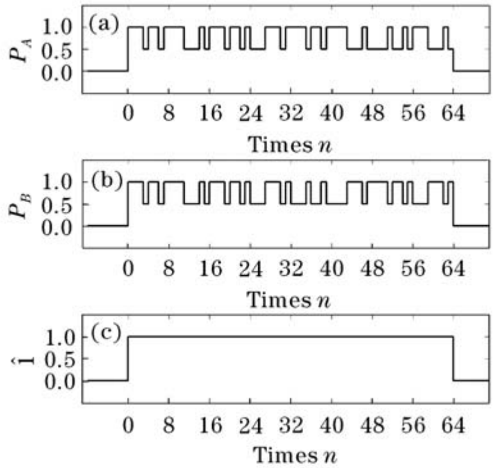

Fig. 4. Three probe signals. (a) and (b) are the 64-bit unipolar code words, and (c) is a 64-bit all-ones code word.

where $\hat{1}$ is the 64-bit of all-ones codeword. The 64-bit P_A, P_B, and $\hat{1}$ are illustrated in Fig. 4.

The three probe signals, P_A, P_B, and $\hat{1}$, are injected at intervals into the fiber, and the backscatter returns of P_A, P_B, and $\hat{1}$ are detected, respectively. The backscatter return is convolution (*) of the probe signal with h_f, the fiber optical impulse response. On reception, the following processing is applied to the returns from the three probe signals[12]:

Step 1: the return from the probe signal P_A is correlated with A, yielding $x^{(1)}$.

Step 2: the return from the probe signal P_B is correlated with B, yielding $x^{(2)}$.

Step 3: the return from the probe signal $\hat{1}$ is correlated with $0.75(A+B)$, yielding $x^{(3)}$.

Finally, the output is defined as

$$
\begin{aligned}
y &= x^{(1)} + x^{(2)} - x^{(3)} \\
&= \mathrm{corr}(A, P_A * h_\mathrm{f}) + \mathrm{corr}(B, P_B * h_\mathrm{f}) \\
&\quad -\mathrm{corr}(0.75(A+B), (\hat{1} * h_\mathrm{f})) \\
&= 0.25 L h_\mathrm{f}. \qquad (7)
\end{aligned}
$$

The output is the fiber backscatter impulse response, which is a curve of backscatter inside the fiber along the distance from source. The resulting resolution of response is similar to the performance of conventional single-pulse OTDR and the response intensity is much stronger than that of the single pulse. Therefore the application of Golay codes significantly increases the dynamic range of the OTDR subsystem without sacrificing response resolution.

The faults of oil pipeline can be identified according to the characteristics of the optical power received by the transmitted optical power-meter. The optical fiber cable is installed along the pipeline for monitoring the oil leakage and external damage. When oil leaks, the cable is soaked in oil or hydrocarbon liquid, it can swell and induce additional attenuation inside the fiber. When the disturbances such as oil leaking, tampering, and mechanical impacting exert influence on the optical fiber cable, the deformation and vibration of the cable can induce additional bending loss inside the fiber. The transmitted optical power will change.

The transmitted optical power O_out of the fiber is monitored in real time by an optical power meter. The three probing signals, P_A, P_B, and $\hat{1}$, are injected into the fiber in sequence. The outputs of P_A, P_B, and $\hat{1}$ are denoted as O_A, O_B, and $O_{\hat{1}}$, respectively. The amplitudes of O_A and O_B are not only modulated by the external disturbances, but also modulated by A and B at the source.

Without considering external disturbances, the amplitude of $O_{\hat{1}}$ is always constant, denoted as O_M. The amplitudes of O_A and O_B alter the states between O_M and $0.5O_M$ companying with the states of A and B. The Golay codes, A and B, are pseudo-random sequences, so it is difficult to remove them by a filter. Therefore, to eliminate the modulation of A and B, the amplitudes of O_A and O_B can be retransformed by a decoder. If the amplitude of O_A or O_B is corresponding to bit -1, it doubles, otherwise it does not change. After being retransformed, the amplitudes of O_A, O_B, and $O_{\hat{1}}$ are only related to the external disturbances, denoted as $O_{\mathrm{out}A}$, $O_{\mathrm{out}B}$, and $O_{\mathrm{out}\hat{1}}$, respectively. For example, a 64-bit unipolar Golay code P_A is injected into the fiber and received by an optical power meter at the other end of fiber. Assuming the fiber being disturbed by an external force, and the Fig. 5(a) illustrates the waveform of the transmitted optical power O_A. After retransformed, the transmitted optical power $O_{\mathrm{out}A}$, as shown in Fig. 5(b), has removed the modulation of A and is only the response of sensing optical fiber cable to the external disturbance.

The types of faults can be identified according to the characteristics of the transmitted optical power that is the response of sensing cable to the external disturbance. Once the optical fiber cable is disturbed by external disturbances, the transmitted optical power will change and the following cases maybe occur: (1) decaying exponentially, which is caused by oil leaking; (2) oscillating, which is caused by mechanical disturbances or oil leaking streams; (3) pulse-down and then return to normal, which is caused by mechanical disturbances; (4) zero, which is caused by fiber break.

Figure 6 shows two typical cases of the response to external disturbances. Figure 6(a) illustrates the

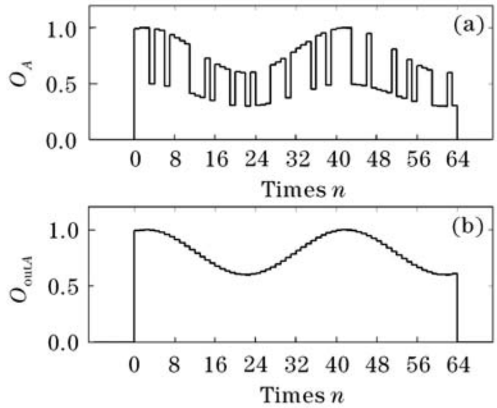

Fig. 5. The waveforms of the transmitted optical power. (a) is a waveform received and (b) is the retransformed waveform of (a).

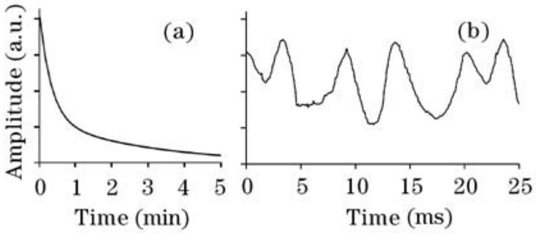

Fig. 6. Responses of sensing fiber to external disturbances. (a) and (b) are the typical waveforms of cases (1) and (2), respectively.

transmitted optical power in our experiment when a 3.6-m-long cable with diameter of 6 mm is soaked in leaked gasoline. The cable absorbed gasoline and swelled significantly in its physical dimensions. The swelling can cause a mechanical deformation of fiber and induce bending-loss. Figure 6(b) illustrates the transmitted optical power disturbed by a 0.6-MP stream leaked from a hole within a pipeline.

After retransformed, the transmitted optical signals, $O_{\mathrm{out}A}$, $O_{\mathrm{out}B}$, and $O_{\mathrm{out}\hat{1}}$, are the true responses to the external disturbances and can be sampled ideally in any rate, such as the same frequency of the Golay codes. The external disturbances can be characterized and analyzed in a wide range of frequency spectrum. In a word, the application of Golay codes to DOFS overcomes the shortcomings of the prototype based on the conventional single-pulse OTDR.

The Golay codes are a pair of complementary sequence codes, and the sum of their autocorrelation is zero for all non-zero shifts. The application of Golay codes can improve the range-resolution performance of OTDR subsystem, which has a better dynamic range by increasing the signal-to-noise ratio of the backscattered light. On the other hand, the application of Golay codes can offer a method to characterize and analyze the transmitted optical power in a wide range of frequency spectrum. The application of Golay codes to DOFS is able to remedy the limitation of the prototype based on conventional single-pulse OTDR.

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