Sensitivity enhancement of distributed polarization coupling detection in Hi-Bi fibers

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The intensity and position of the coupling points in high birefringence (Hi-Bi) fibers can be detected effectively using distributed polarization coupling (DPC) detection. The detection sensitivity can decrease due to mechanical vibration disturbance and environment noise. Thus, a method based on empirical mode decomposition is proposed to detect weak mode coupling points. The simulation and experimental results illustrate that the proposed method can suppress the noise effectively and improve sensitivity significantly. The method can identify coupling points as weak as –60 dB embedded in noise automatically and effectively. The algorithm is applicable for DPC, and the experimental sensitivity is improved by 10 dB.

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High birefringence (Hi-Bi) fibers are used in many areas related to fiber optics, including coherent optical communications, integrated-optic devices, and optical sensors based on interferometric techniques. Distributed polarization coupling (DPC) detection employs white-light interferometry (WLI) in Hi-Bi fibers, and is widely used in the measurements of strain, twist, temperature, and many other physical parameters[1−3]. Due to high spatial resolution and wide dynamic range brought about by the adoption of WLI[4], the intensity and position of the coupling points can be detected effectively.

Mechanical vibration disturbance and environment noise can lead to the degradation of detection sensitivity of DPC[5,6]. Therefore, the weak coupling points are submerged in noise, leading to a wrong diagnosis. To date, phase modulation, differential signal detection, or rotation angle optimization can be employed for weak coupling measurement[7−9]; however, the complexity of the required system has also increased. In order to increase the detection sensitivity, some signal analysis methods, such as band-pass filtering[10] and the wavelet transforms[11], have been reported for noise reduction. The main drawback, however, is that the base functions are fixed, and no such function has been proposed to correspond to the features of the acquired signals. In comparison, the empirical mode decomposition (EMD) is a highly efficient technique for processing nonlinear and non-stationary signals, because the procedure is data-driven, adaptive, and not restricted by linearity or priori conception[12]. Gong *et al.* applied EMD and the threshold method to reduce the noise in the lidar signals[13]. Deng *et al.* used EMD and local entropy to detect small targets[14]. Here EMD combined with DPC is proposed to enhance the detection sensitivity and realize the distributed weak mode coupling measurement.

The scheme of DPC detection is shown in Fig. 1. A superluminescent diode (SLD) emitting at 1 328 nm was used as the light source. An in-line polarizer was fusion spliced in front of the Hi-Bi fiber. Its polarization orientation was aligned to the slow axis of the polarization maintaining fiber (PMF), so that only the slow axis was excited. The output light from the fiber was collimated, passed through a rotatable half wave plate and analyzer, and then injected into the scanning Michelson interferometer. The interference signal was detected with the photodiode (PD). If the polarization direction of the incident polarized light was the same as one of transmission axis in the Hi-Bi fiber, then only the light of this kind of polarization mode E_0 was transferred within the fiber. When there was one coupling point, polarization coupling occurred and some of the light were coupled to the orthogonal polarization state, such as E_x and E_y, as shown in Fig. 1.

Considering the optical path difference (OPD) fluctuation rand(Δd) caused by the Michelson interferometer, the output strength of the spectral interferogram can be expressed as

$$\begin{aligned} I_{\text{out}} = {} & I_{\text{o}}\{1+\exp[-((d+\text{rand}(\Delta d))/L_{\text{c}})^2]\} \\ & \cdot\cos\{k_{\text{o}}[d+\text{rand}(\Delta d)]\} \\ & +\sqrt{h-h^2}\exp\{-L_{\text{c}}^2[d+\text{rand}(\Delta d)]^2/2\} \\ & \cos\{\Delta\beta l-k_{\text{o}}[d+\text{rand}(\Delta d)]\}, \end{aligned} \quad (1)$$

where I_{o} is the DC component of the interference, L_{c} is the coherence length of the light source, d is the OPD of the scanning Michelson interferometer, k_{o} is the wave number in free space, h is the power coupling strength parameter, l is the fiber length between the coupling point

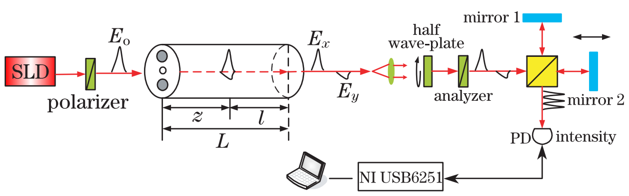

Fig. 1. System schematic of DPC detection.

and the output end of the fiber, and $\Delta\beta$ is the propagation constant difference of the two eigenmodes.

The relation between the strength of the polarization mode coupling and the output strength of the spectral interferogram can be expressed as[15]

$$h = 10\log(I_{\mathrm{cf}}/I_{\mathrm{main}})^2, \tag{2}$$

where I_{main} represents the amplitude of interference fringe when the OPD is zero, and I_{cf} is the amplitude of zero order fringe in the interference packet.

Under ideal conditions, the fringe contrast becomes constant with a value of 1.0. Thus, I_{main} can be equal to I_0, where I_0 is the DC component of the interferogram.

In actual data processing, the coupling strength is usually calculated by[6]

$$h = 10\log(I_{\mathrm{cf}}/I_0)^2. \tag{3}$$

The practical acquired interferogram coinciding with Eq. (1) is shown in Fig. 2. There is a sudden-change structure in the detailed drawing, which shows the nonlinear and non-stationary feature existing in the signal.

The EMD-based method based on the signal characteristics of DPC is proposed in this letter. The major advantage of EMD is the posteriori adaptation, because the intrinsic mode functions (IMFs) are derived from the signal itself. The original signal $x(t)$ can be expressed as follows using the EMD method:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t), \tag{4}$$

where $c_i(t)$ is IMFs, i is the number of the corresponding IMF, and $r_n(t)$ is the residue component.

EMD acts as a set of filters that decomposes the original signal from high to low frequency. We assume that high-frequency IMFs contain only noise and turbulence. This is a conservative estimation, because those IMFs may contain useful signals. Although the energy of the high frequency IMFs are of little value, signal-to-noise ratio (SNR) can still be improved by subtracting high-frequency modes from the data.

The next task ahead is to choose useful IMFs to reconstruct the signal. According to Eq. (3), the coupling intensity of the central interferential packet is 0 dB under ideal conditions. The above simple condition is applied as the selection criterion. However, in practice, I_{main} is not equal to I_0, and the coupling intensity calculation can

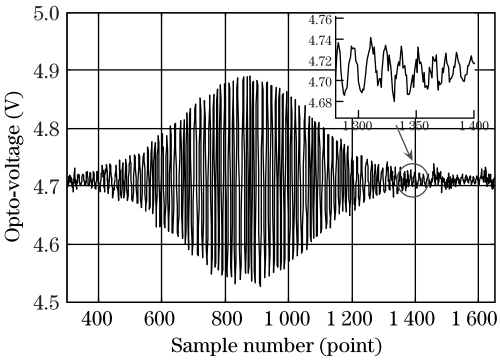

Fig. 2. Practical acquired interferogram.

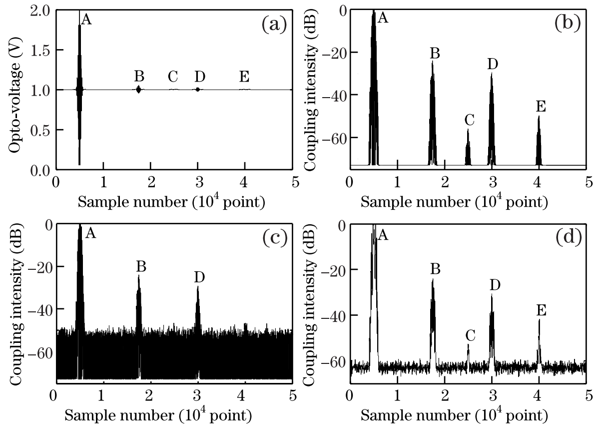

Fig. 3. Simulation results of (a) the original signal without noise, the coupling signals (b) without and (c) with noise, and (d) EMD-based method.

cause errors that can be identified using Eq. (3). Thus, the selection criterion is then revised as $10\log(1/k)^2$ dB in the central interferential packet, where k is the interference visibility.

We considered four coupling points in the Hi-Bi fiber and an interferogram signal without noise. The original interferogram signal without noise is simulated in Fig. 3(a) and its coupling intensity is plotted in Fig. 3(b). Then, random noise was added to the original signal. Figure 3(c) shows the coupling intensity of the noisy signal, whereas Fig. 3(d) shows the de-noising performance using the EMD-based method.

The EMD-based method can suppress the noise effectively and improve the detection sensitivity significantly. The detection sensitivity improves from –50.48 to –62.74 dB. All the coupling points can be detected effectively with the corrective positions and intensities. The IMF components from IMF1 to IMF6 have been removed automatically with the proposed selection criterion.

The experimental setup is shown in Fig. 1. The SLD-101 of General Photonics Company emitting at 1 328 nm was used as the light source. Its spectrum followed a Gaussian distribution, and the 3-dB spectral width was approximately 35.8 nm. The USB 6 251 of National Instrument was used for data acquisition. The scanning speed of the step motor with mirror2 was 0.75 mm/s. A Hi-Bi fiber with four coupling points caused by stress was tested. The data averaging method was also used for comparison and analysis.

Figure 4 shows the experimental results. Figures 4(a), (b), and (c) denote the signal embedded in noise, the de-noised signal with the data averaging method and the proposed EMD-based method, respectively. The noisy signal attains detection sensitivity of –48.25 dB. As can be seen, A is the coupling interference fringe when the OPD is zero, whereas B, C, D, and E are the coupling points in the Hi-Bi fiber.

The detection sensitivities obtained by data averaging and EMD-based method are –60.08 and –52.49 dB, respectively. The signal was decomposed into 20 IMFs, and 5 IMFs (IMF1–IMF5) were removed from the data.

The EMD enhancement shows better noise-suppressing performance than the method of 100-point averaging, which requires a comparatively large quantity of data on

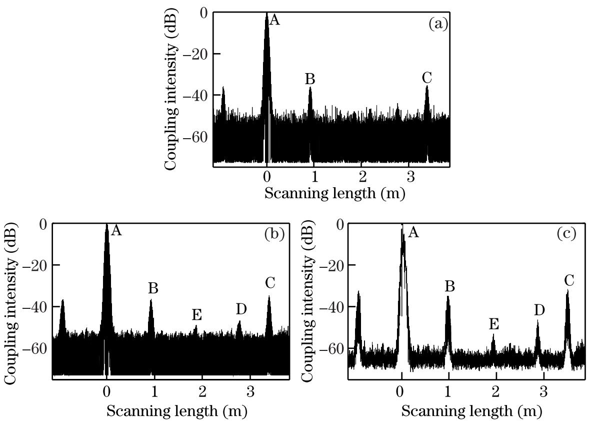

Fig. 4. Experimental results of (a) noisy signal, (b) 100-point data averaging, and (c) EMD-based method.

average. Furthermore, the weak coupling points D and E, which are difficult to detect become clearer, indicating that even when the signal is embedded in heavy noise, it can still be extracted with the proposed method.

In conclusion, a simple EMD-based method in conjunction with DPC is presented. The output interferogram data from the simulations and experiments are analyzed. A comparative study between our procedure and data averaging is performed. The result shows that the EMD-based method can suppress the noise effectively and identify the coupling points embedded in noise automatically. The gain of experimental detection sensitivity also exceeds 10 dB.

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