Localization theory of distributed fiber vibration sensor

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Based on Sagnac interferometer, a simple distributed optical fiber sensing system with sub-loop is presented to monitor the vibration applied on the sensing fiber. By introducing a sub-loop, three output beams of interference with different delay time are gotten. Location of the vibration is analyzed through mathematical-physical equations. The vibration frequency, amplitude, and location are theoretically simulated. The results agree well with the previous experiments.

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In recent years, distributed optical fiber sensor has received many attentions in breakage alarm of pipelines or in trespassing alarm on the restricted area[1−3]. Distributed fiber interferometers of Sagnac and Mach-Zehnder configurations have been researched deeply because they are sensitive to tiny vibrations caused by any action of trespassing or breakage[4−7]. Many methods have been adopted to improve its performance, but complex signal processing is needed[8,9]. Omori *et al.* proposed a simple distributed vibration sensing system based on fiber Sagnac interferometer[10]. In the system, an additional sub-loop fiber is introduced to the fiber Sagnac interferometer as the delay fiber ring. Traveling in the sub-loop fiber, two interference beams were gotten with different time delays according to their paths in sub-loop fiber. Although vibration information is involved in intensity and phase of these beams, the location demodulation of the signal remains unsettled[10].

In the system proposed by Omori *et al.* (see Fig. 1), clockwise (CW) and counter-clockwise (CCW) lights pass through the sensing fiber ring and sub-loop fiber before they interfere with each other. In this way, the system can be unfolded into several equivalent Sagnac interferometers according to their optical paths in the sub-loop, as shown in Fig. 2. The equivalent Sagnac interferometers are different in optical path, which corresponds to the turns the light travels in the sub-loop. That is to say, $n = 0$ corresponds to the situation that neither CW nor CCW light enters into the delay fiber loop, while $n = 1$ and $n = 2$ mean both of them enter into the delay fiber for 1 and 2 turns, respectively. Thus there are three output interference signals corresponding to three equivalent Sagnac interferometers.

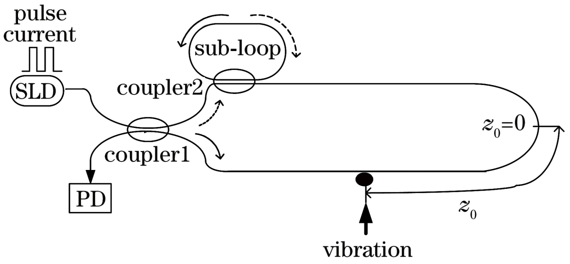

Fig. 1. Distributed vibration sensor system with a sub-loop of delay fiber[10]. SLD: superluminescent diode; PD: photodetector.

Supposing that the intensities of both CW and CCW light beams are I_0, the vibration position is applied at the distance z_0, the phase difference induced by vibration between CW and CCW lights is $\theta(t)$, n is the times of light traveling in the sub-loop, the interference output is expressed as

$$P_n(\tau) = \frac{1}{2^n} I_0 \left|1 + \cos(\theta(\tau_n + \delta_n) - \theta(\tau_n - \delta_n))\right|, \quad (1)$$

$$\tau_n = t - \frac{L_0 + nL_1}{2c}, \quad (2)$$

$$\delta_n = \frac{z_n}{c} = \frac{z_0 + nL_1/2}{c}, \quad (3)$$

where L_0 and L_1 are the lengths of the sensing fiber and the sub-loop, respectively, c is the speed of light in the fiber, z_n is corresponding to the location of the applied vibration and can be represented as $z_n = z_0 + nL_1/2$. By filtering direct current (DC) component in Eq. (1), we can get

$$P_n(\tau) = \frac{1}{2^n} I_0 \cos(\theta(\tau_n + \delta_n) - \theta(\tau_n - \delta_n)). \quad (4)$$

Supposing that A and f are the amplitude and frequency

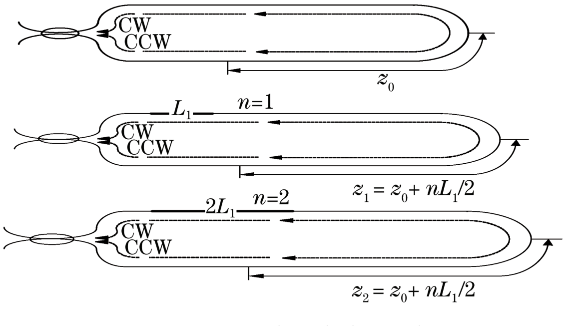

Fig. 2. Equivalent light paths.

of vibration, then

$$\theta(t) = A\cos(2\pi f t). \quad (5)$$

If A is small enough, Eq. (4) can be derived as

$$\begin{cases} P_0 \propto -2K\sin(2\pi f\delta_0) = -2K\sin(2\pi f\frac{z_0}{c}) \\ P_1 \propto -\frac{1}{2}K\sin(2\pi f\delta_1) = -\frac{1}{2}K\sin(2\pi f\frac{z_0+L_1/2}{c}) \\ P_2 \propto -\frac{1}{8}K\sin(2\pi f\delta_2) = -\frac{1}{8}K\sin(2\pi f\frac{z_0+L_1}{c}) \end{cases}, \quad (6)$$

where K is a linear coefficient, and the output changes with the time variant τ_n, which is related to both vibration frequency f and location z_n.

Letting

$$\begin{cases} D_1 = 4P_1/P_0 \\ D_2 = 16P_2/P_0 \end{cases}, \quad (7)$$

then

$$z_0 = \frac{L_1 \cdot \tan\frac{2D_1^2-D_2-1}{\sqrt{4D_1^2-(D_2+1)^2}}}{2\arccos\frac{D_2+1}{2D_1}}. \quad (8)$$

In this way, the vibration location z_0 can be solved according.

Omori *et al.* have proved that when a vibration is applied at different position, the rate of amplitude voltage V_0/V_1 is different, as shown in Fig. 3. It cannot make sure exactly where the vibration is through the graph. We give the localization theory in this letter, and perform the simulation to verify its validity.

Supposing that the vibrations with different frequencies of 500 and 1000 Hz are applied on the same location of $z_0 = 4.0$ km, the simulation results are shown in Fig. 4.

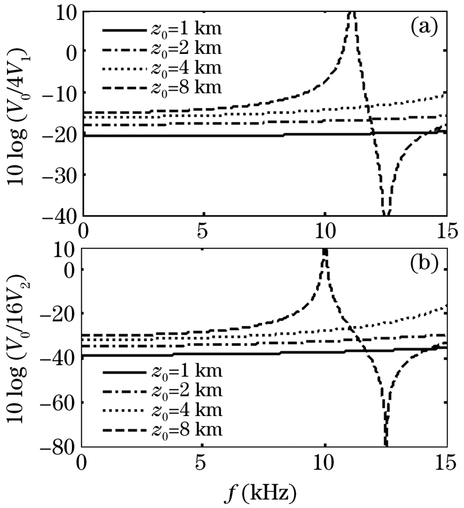

Fig. 3. Ratio of different vibration points.

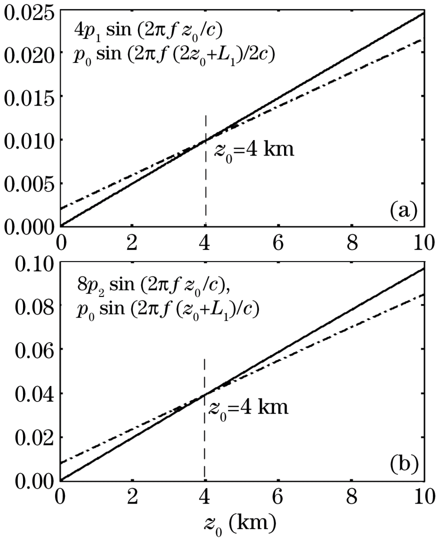

Fig. 4. Localization with different frequencies of (a) 500 Hz and (b) 1 kHz.

P_0 and P_1 have an intersection point, so do P_0 and P_2. Both of them intersect at the vibration point z_0. Furthermore, all of the amplitudes can intersect at the same point with different frequencies. It is obvious that the localization of z_0 is accurately demodulated.

In conclusion, the location theory of distributed vibration sensing system of a simple Sagnac interferometer with a sub-loop is derived theoretically. The demodulation theory of location is relatively simple and its validity is demonstrated with stimulation. The experimental results will be reported in the future.

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