55.6: Enhanced Multiplexing Capacity of Low-Coherence Reflectometric Sensors Based on a Loop Topology

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Abstract

A novel scheme for enhancing the multiplexing capacity of low-coherence reflectometric sensors is demonstrated. The scheme is based on connecting the sensing elements in serial in a loop configuration, allowing each of the sensors within the array being interrogated twice from opposite directions. The bi-directional interrogation doubles the multiplexing capacity while maintains the signal to noise ratio. The double interrogation scheme would allow the normal operation of the sensor array even when one end of the transmission fiber were broken, improving the reliability of the sensing system for large-scale structural monitoring.

Key Words: Low-coherence reflectometry, fiber optic sensors, quasi-distributed sensors, strain sensors.

I. INTRUDUCTION

Optical low-coherence reflectometry (OLCR) [1,2] has emerged as high-resolution measurement technique for optical device testing [3-6]. OCLR is based on the use of low coherence light source and a scanning optical (Michaelson) interferometer to match the optical paths of the reflected waves from the device under test. OCRL has been applied for quasi-distributed sensing [7-14] by intentionally introducing partial reflectors along an optical fiber. The gauge lengths of the sensors (defined between two partial reflectors) are chosen to be longer than the coherence length of the source so that the reflected waves from the two end-faces of a sensing gauge would not mix coherently before reaching the scanning interferometer. An interferogram appears at the output of the scanning interferometer only when its optical path difference (OPD) is matched to the gauge length of a particular sensor. A series of interferometric maximums or peaks is resulted when the OPD of the interferometer is scanned through all the possible gauge lengths of the sensors. The positions of the peaks can then be used as measures of the gauge lengths of the sensors.

This paper reports a scheme that can enhance the multiplexing capacity of low-coherence reflectometric sensors. The scheme offers larger multiplexing gain, higher reliability over the conventional reflectrometry sensor array. The higher reliability is achieved through the use of bi-directional interrogation of each sensor in the array, which provides an extra degree of redundancy and is important for embedded applications in large-scale smart structures.

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II. DESCRIPTION OF THE SCHEME

The proposed multiplexing scheme is shown in Fig.1. Low coherence light from an Er-doped ASE source is coupled into a fiber Sagnac loop through a 3dB coupler. The fiber loop contains a serial connected sensor array S_1, S_2, ...S_N, with each one of them (S_i) being defined in-between two partial reflectors i and $i+1$. The gauge lengths of the sensors (denoted as $l_{i,i+1}$ for S_i) are chosen to be approximately equal but slightly different from each other. There are four reflected waves from the two ends of sensor S_i, two reflected back toward end *A* (CW) and the other two toward end *B* (CCW). The four waves are guided back through the 3-dB coupler to a Michelson interferometer with its output monitored by a photo-detector (PD). The optical path difference (OPD) of the interferometer is set to be approximately equal to the sensor gauge length ($l_0 \approx l_{i,i+1}$ for i=1, 2, ...N) and can be varied through the use of a scanning mirror as shown in Fig.1.

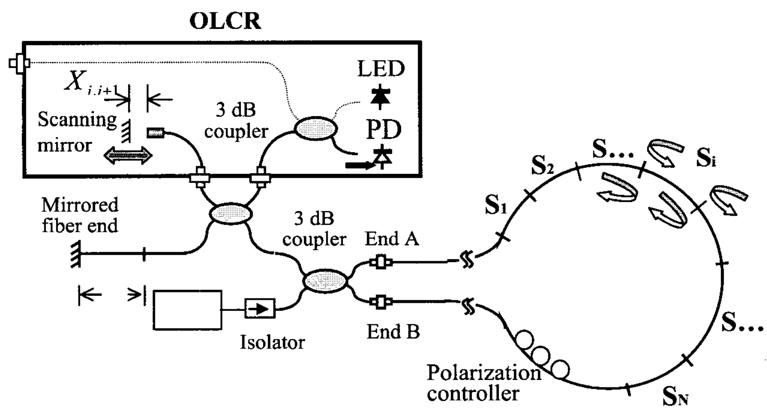


Figure 1 *Schematic of enhanced-multiplexing fiber optic sensor array loop.*

In Fig.1, the LED and the part with dotted line are not used. The components within the box are part of the commercial precision reflectometer (HP8504B), and we only used the scanning mirror and the photo-detector within the box. When the mirror is scanned, there will be N groups of interference fringes corresponding to the OPD of the interferometer matched to that of the *N* sensors in the loop, the peak intensity at the photo-detector corresponds to the *i*-th sensor may be written as

$$I_D(i,i+1) = \frac{I_0}{16}\sqrt{R_f R_m \eta(X_{i,i+1})}\left\{\left[\prod_{k=1}^{i-1} T_k \beta_k\right]^2 \sqrt{R_i R_{i+1} T_i \beta_i} + \left[\prod_{k=i+2}^{N+1} T_k' \beta_k'\right]^2 \sqrt{R_i' R_{i+1}' T_i' \beta_i'}\right\} \quad (1)$$

Where I_0 represents the light intensity coupled into the input optical fiber. The insertion losses of the 3-dB coupler has been neglected. β_i represents the excess loss associated with connection loss between the sensing segments. T_i and R_i are respectively the transmission and reflection coefficient of the *i-th* partial reflector. T_i is in general smaller than $1-R_i$ because of the loss factor β_i. $\eta(X_{i,i+1})$ is the loss associated with the scanning mirror and collimating optics and is a function of the scanning mirror position $X_{i,i+1}$. R_f and R_m are the reflectivities of the mirrored fiber end and scanning mirror, respectively. β_i', T_i', R_i' represent, respectively, the loss, the transmission and the reflection from the counter clockwise (CCW) direction. The two terms within the bracket correspond respectively the CW and the CCW light.

III. MULTIPLEXING CAPACITY EVALUATION

In the ring fiber optic sensor array the fraction of optical source power coupled into the fiber and distributed it over the sensor array via several connectors. Each sensor elements absorbs or diverts a certain amount of power (insertion loss), typically between 0.1 dB and 0.5 dB. If the minimum-detecting limit of the photodiode is $I_{\min}$, then, the maximum number of the total fiber optic sensors can be evaluated by the condition

$$I_D(i, i+1) \geq I_{\min} \tag{2}$$

For convenience calculating, we neglect the excess insertion loss of the 3dB couplers and assumed that the typically fiber optic connection insertion loss coefficient $\beta_i = 0.9$ (i = *0, 1, 2,..., N*). For good connected fiber ends, the air gap is smaller then the wavelength, in that case the typically reflectivity R is nearly equal to 1%. Therefore, the transmission coefficient can be calculated as $T_i = 0.89$. We assume that the average attenuation of the collimating optics over the whole scanning range is 6 dB, i.e. $\eta(X_{i,i+1}) = 1/4$. Then, compare with the loop open case, the sensor multiplexed capability is enhanced as twice as before, as shown in Fig. 2.

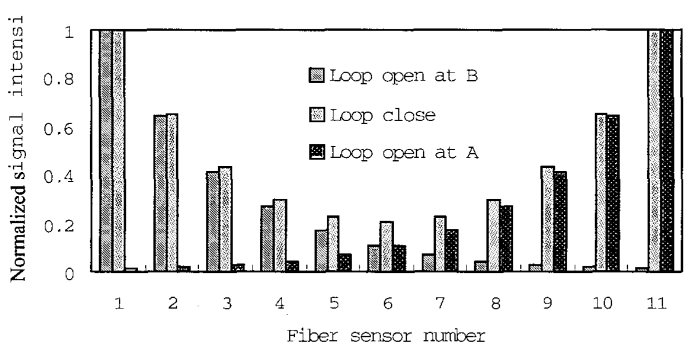


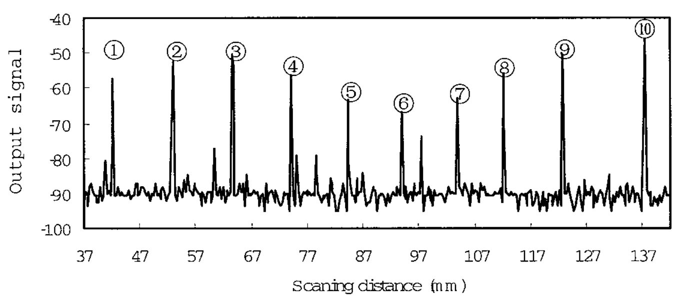
Figure 2 *Output signal intensities comparison between sensor array connected in a fiber loop and in a fiber line.*

Generally, in fiber optic sensing system, the typical detecting capability of the photodiode is about 1 *nW*. Taking into account the noise floor and other stray signals from the system, the reasonable detect limit is assumed that $I_{\min} = 10\,nW$. Under the condition (2) and take account of the above data, for light source power $I_0 = 0.3\,mW$, the maximum number of the fiber sensor can be calculated as $N_{\max} = 20$ in loop close case and $N_{\max} = 9$ in loop open case, respectively.

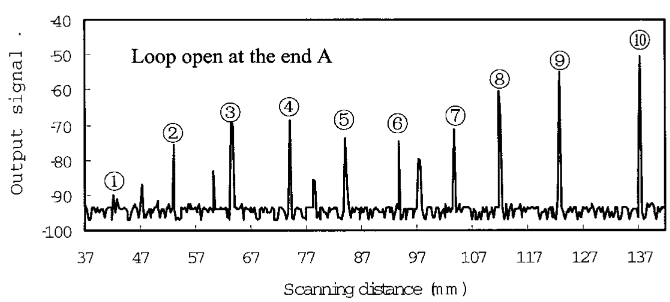
In fact, the maximum number of total fiber optic sensors is not only depend on the light source power level, but also limited by the length of the longest moving distance of the scanning mirror (or the length of translation stage). In addition, it should be noted that the receiver noise floor, and hence the detecting sensitivity, will be a function of the method of signal encoding and the required scanning speed of the moving mirror. Thus, the maximum number, N_{max}, of sensors are less then that given in above paragraph.

IV. EXPERIMENTAL RESULTS

Fig.1 shows the experimental arrangement used to demonstrate the ring-link fiber optic white light interferometric sensor system. An ASE (amplified spontaneous emission) light source with a spectral width of about 20 nm at central wavelength 1.55 μm was used in our experiment. The unpolarized light power of the ASE source is adjustable in the range of 0~10mW. 10 optical fiber segments were used as fiber optic sensor and each sensor gauge length was chosen nearly 1 meter. The difference of each sensor gauge length is about 10 mm, and connected each other by temporary connectors. The 10-sensor array signals intensity characteristics were given in Fig.3 for both case of ring-link and ring-open at end A (or end B), respectively. For source power level of –4.63dBm (0.34mW). Qualitatively, it is agreement with the theoretical analysis results of Fig.2, and it can be seen that the high of the signal peak is different between Fig. 2 and Fig. 3. In fact, it is difficult to ensure the reflectivity of each fiber segment same as one value.



(a) Loop closed case: 10 fiber optic sensors array output signals with light source power –4.63 dBm



(b) Loop opened case: only can see 9 of 10 fiber optic sensors array output signals with light source power –4.63 dBm

Figure 3 *Characteristics of 10 fiber optic sensors array output signals in both loop-close and loop-open cases.*

The output signals floor were polarization-independent in case of ring-open. The polarization noise comes into being the ring-link. In order to reduce the noise generated by the change of polarization state, a polarization controller was utilized in the fiber ring. The improved noise floor signals are plotted in Fig. 4.

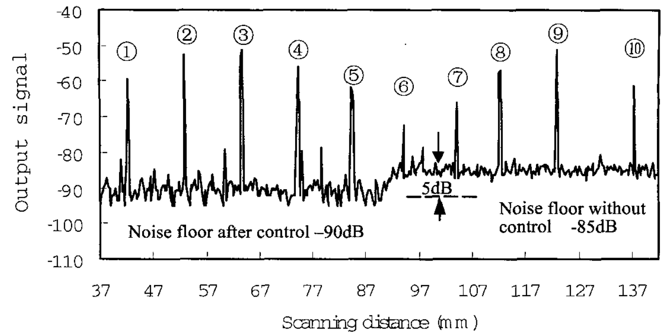


Figure 4 *A 5 dB in noise floor is improvement by a polarization controller.*

V. SUMMARY

A fiber optic white light interferometric sensor multiplexing enhancement technique has been proposed and demonstrated. A practical implementation of this technique is presented which makes use of a optical low-coherence reflectometer (OLCR) and standard single mode fiber. The sensor array ring-link topology is completely passive and absolute length measurements can be obtained for each sensing fiber segments. The proposed sensing scheme can be used to measure quasi-distribution strain or temperature. For the large-scale smart structure, this technique not only extends the multiplexing potential, but also provides a redundancy for the sensing system. It is mean that the sensor loop permit one point breakdown, because the sensing system will still working whenever the embedded sensor array break in somewhere.

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