Rangeability extension of fiber-optic low-coherence measurement based on cascaded multistage fiber delay line

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We demonstrate a simple method to extend the measurable fiber length with a fiber-optic low-coherence technique. This method is based on a cascaded structure of multistage fiber delay line laid in one arm of the low-coherence technique. By choosing different individual stages in the cascaded fiber delay line, the length of the fiber under test can be continuously measured with a different measurement range. The measurement range of 0.81 km and spatial resolution of 60 μm are successfully realized. © 2012 Optical Society of America

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1. Introduction

The fiber-optic low-coherence technique, also called the optical low-coherence reflectometer (OLCR), has important applications in many fields such as fiber-optic sensing and optical coherence tomography (OCT) [1,2]. The traditional OLCR can measure length within 1 m with spatial resolution in the tens of micrometers. The maximum measurable length is limited by the scanning range of the mechanical mirror, and the spatial resolution is determined by the spectral width of the light source [3]. In order to characterize the fiber delay line, measurement resolution within several micrometers (μm) may be needed. Recently, we reported a simple fiber-ring structure to enhance the measurement resolution of OLCR by multiplying the fiber under test (FUT) [4]. A resolution of about 3 μm was experimentally obtained at the cost of measurement range. So far, many efforts have been employed to extend the measurement range of OLCR. For instance, a Fabry–Perot resonator with recirculating delay was used to achieve more than 150 m range with resolution of about 200 μm [5,6]. Its transmission, however, degrades at a rate of 0.175 dB per recirculating order; moreover, a precisely tuned temperature chamber is required in order to change the cavity's optical path and thus select the proper recirculating order. Other fiber delay line structures were also used to extend the measurement range, but its largest measurement range is only about 10 m [7,8]. For a certain applications, such as a calibration total station [9,10], it is usually requested to calibrate the 1 km range with measurement resolution better than 0.15 mm [11]. This performance can also find many other applications in in-service fiber line identification in a complex fiber network, fiber chromatic dispersion measurement, and long distributed fiber-optic sensors [12]. For example, a complex fiber network usually comprises many long fiber cables connected together with fiber amplifiers by fiber adapters. High spatial resolution measurement is a basic requirement to diagnose the trouble spots.

In this paper, we demonstrate a cost-effective method to extend the measurable range of fiber-optic

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low-coherence measurement by use of an easily configured multistage fiber delay line. A commercial OLCR (HP8504A precision reflectometer) is used as the fiber-optic low-coherence measurement instrument. In this method, a cascaded fiber delay line in a ring structure is inserted in one arm of the instrument and thus the original measurement range of the instrument is extended by more than 2000 times. In experiment, we have achieved performance of 60 μm spatial resolution and 0.81 km measurement range. It is noted that this method can cover the whole measurement range without any blind zone, and it is suitable for any kind of fiber-optic low-coherence measurement instrument.

2. Principle

A fiber-optic low-coherence measurement system is usually originated from a Michelson interferometer configuration with a broad-bandwidth laser serving as the light source. When the difference in optical paths between the reference and test arms falls into the coherent length (generally several tens of micrometers) of the light source, interference will occur. By scanning the movable mirror set in the reference arm, the fiber length in the test arm within a short range (such as less than 1 m) will be properly detected.

To extend the measurable range of the fiber-optic low-coherence measurement, we design a cascaded fiber delay line as a ring structure laid in the reference arm (the above port of a 2×2 coupler), as shown in Fig. 1. The light wave passes from port 2 to port 3 of a circulator, enters into the cascaded fiber delay line, and returns to port 1 of the circulator and to the photodetector (PD) through the 2×2 coupler. The cascaded fiber delay comprises N splitting arms and K cascaded stages, in which two pieces of $1 \times N$ couplers are laid in the two ends and several $(N+1) \times (N+1)$ couplers are in the middle. In each $(N+1) \times (N+1)$ coupler, only $N \times N$ ports are used in the cascaded fiber delay line while the other two ports are left for preliminary characterization of the fiber delay line, which will be described as follows. In the other port of the 2×2 coupler, we set a fiber segment noted as FUT_0 equal to the total length of the "0" arms of the cascaded fiber delay line, which is in

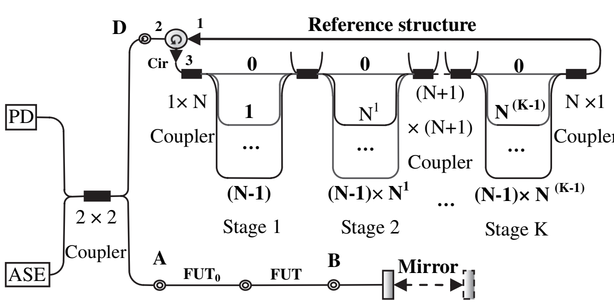

Fig. 1. Experimental setup of the proposed structure: Cir, circulator; FUT, fiber under test; FUT_0, a fiber segment with length equal to the cascaded "0" arms in all stages; Mirror, movable mirror; A and B, ports of test arm; D, port of the reference arm.

series connected with the FUT and the movable mirror. The cascaded fiber delay line can provide large absolute fiber length as reference; thus the measurement range can be extended correspondingly.

In the multistage fiber delay line structure, the length difference between two adjacent arms in the same stage is set approximately equal and covers the total measurement range. In the first stage, the length difference between two adjacent arms is just less than the original measurement range (L_0). In the Kth stage, the length between two adjacent arms is equal to $N^{(K-1)} \times L_0$. The maximum measurement range for the fiber delay line with K stages and N arms can be expressed by

$$L_{\text{measurement}} = N^K \cdot L_0, \tag{1}$$

which results in an extension of measurement range by N^k.

To estimate the maximum extension, we need to investigate the relationship between the signal-to-noise ratio (SNR) of the fiber-optic low-coherence measurement and the optical loss existing in the reference ring structure. Figure 2 shows the experimental result, where the optical loss of the reference ring is induced by an attenuator substituted for the cascaded fiber delay line (see the inset of Fig. 2). When the optical loss is increased to 56 dB, the SNR of the fiber-optic low-coherence measurement decreases to about 10 dB, which is the minimal value required for detection. Supposing no excess insertion loss of the couplers, the optical loss in the N-arm and K-stage fiber delay line can be presented as

$$\text{Loss(dB)} = 10 \times \log[N^2 \times (N+1)^{K-1}]. \tag{2}$$

We calculate the optical loss of the ring structure according to Eq. (2), and the measurement range according to Eq. (1). Figure 3 summarizes the

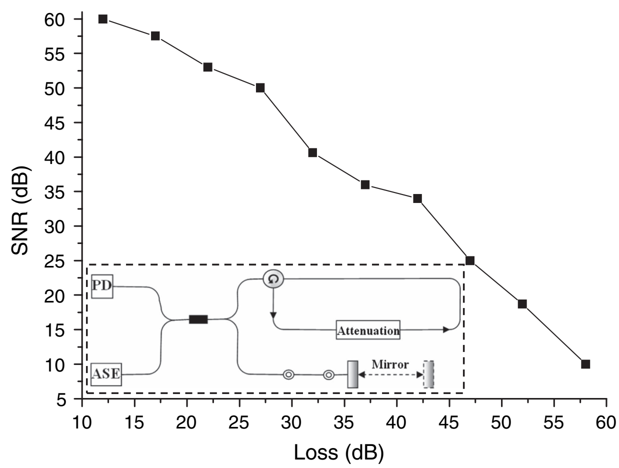

Fig. 2. SNR as a function of the fiber loss in the fiber ring where an attenuator is used to simulate the loss of the proposed structure. The measurement setup is schematically shown in the dashed box.

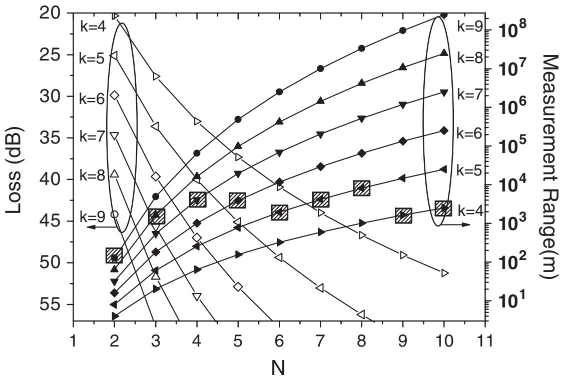

Fig. 3. Optical loss (left scale) and measurement range (right scale) as a function of the splitting number N (from 2 to 10) for different stage numbers K (from 4 to 9). The optimized condition for each N is marked in filled squares.

calculated results of the optical loss (open symbols) and the measurement range (solid symbols) as functions of the splitting number N (from 2 to 10) for different stage number K (from 4 to 9), respectively. We set 56 dB as a threshold loss, and we found that for each N, there is an optimum K to achieve the best performance marked with solid squares. When N equals 2, the optimum $K = 9$ and the largest extension (N^K) is $2^9 = 512$. Similarly, we can get the largest extension as $3^8 = 6561$, $4^7 = 16384$, $5^6 = 15625$, $6^5 = 7776$, $7^5 = 16805$, $8^5 = 32768$, $9^4 = 6561$, and $10^4 = 10000$ for the splitting number $N = 3$–10, respectively. In experiment, we choose $N = 3$ and utilize 1×3 and 4×4 fused couplers in the cascaded fiber delay line. This is because the setting of $N = 3$ results in the maximum delay for any given number of fiber segments [13] and consequently extends the measurement range in the most efficient way.

3. Experiment

In this study, an HP8504A precision reflectometer is used as a fiber-optic low-coherence measurement instrument, which has a measurement resolution of 30 μm (in air), and the measurement range is 400 mm (in air). According to the above analysis (see Fig. 3), it could be a designed eight-stage fiber delay line for $N = 3$ with extension of the measurement range up to 6561. However, because of the insertion loss of the couplers, we could have only configured the seven-stage cascaded structure, and the maximum obtainable extension of the measurement range is 2187.

We configured the first stage of the cascaded fiber delay line and set the length difference (L_0) between two adjacent arms of the first-stage delay line slightly less than the original measurement range, that is, $L_0 = 350$ mm in air. The configured first stage with total range was used for monitoring the length difference between the two arms of the second stage. Similarly, we configured the other Kth stage fiber delay line based on all the previously configured ($K - 1$) stages. This configuration ensures that the length difference between two adjacent arms of the Kth stage is slightly beyond the maximum length of all the previous $K - 1$ stages, which can avoid any blind zone.

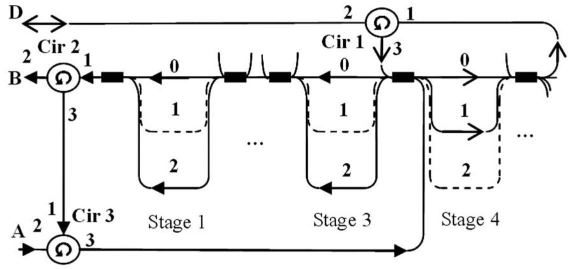

Fig. 4. Schematic of preliminarily characterization. Dashed curves correspond to the "OFF" state, and solid curves correspond to the "ON" state. A, B, and D are the ports of the instrument, as indicated in Fig. 1. Circulators (Cir) are used to form two circle rings for the test and reference arms of the instrument for characterization of the fiber lengths of all separate arms stage by stage.

Besides, the above configuration provides an easy way to preliminarily characterize the absolute length of all stages. The fiber lengths of all arms in all stages and the corresponding spatial resolutions are precisely characterized one by one. All the stages of the fiber delay lines were manually switched between the status of "ON" or "OFF." The average process for multiple measurements was carried on to eliminate the measurement uncertainty.

The experimental setup of preliminarily characterizing stage 4 is schematically depicted in Fig. 4 as an example. Every arm of all stages comprises two states of "ON" and "OFF," respectively. Three circulators (Cir 1, Cir 2, and Cir 3) are used to form two circle rings for the test and reference arms of the instrument, respectively. The preliminary characterization includes two steps. First, the "0" and "1" arms of stage 4 are both connected to the reference arm, and all the "0" and "2" arms of stages 1–3 are in series connected to the test arm. Two interference signals observed in the instrument are illustrated in Fig. 5(a). The left one corresponds to the interference between the "0" arm of stage 4 and all the "0" arms of stages 1–3; the right one corresponds to that between the "1" arm of stage 4 and all the "2" arms of stages 1–3. Their distance can be used to characterize the fiber length of the "1" arm of stage 4. Second, the "1" and "2" arms of stage 4 are both connected to the reference arm, and all the "0" and "2" arms of stages 1–3 are in series connected to the test arm. Besides, a fiber segment with the length approximately equal to the "1" arm of stage 4 is additionally connected to the test arm, which ensures that the right interference signal in Fig. 5(a) can move to the left side while the interference signal between the "2" arm of stage 4 and all the "2" arms of stages 1–3 appear in the right side. The experimental result shown in Fig. 5(b) confirms this procedure. The fiber length of the "2" arm of stage 4 is evaluated by the summation of the two peaks' distance and the "1" arm of stage 4 characterized in the first step. Similarly, the lengths of all seven stages can be preliminarily characterized and are summarized in Table 1.

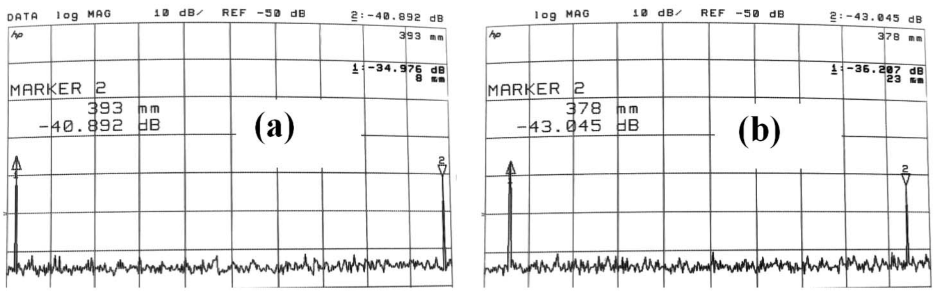

Fig. 5. Examples of the preliminary characterization results of the fourth stage. The vertical scale is 10 dB/div. (a) The left peak is the interference signal of the "0" arms of the 1–3 stages and the "0" arm of the fourth stage, and the right peak is the interference signal of the "1" arm of the 1–3 stages and the "1" arm of the fourth stage. (b) The left peak is the interference signal of the "0" arms of 1–3 stages and the "1" arm of the fourth stage, and the right peak is the interference signal of the "2" arms of 1–3 stages and the "2" arm of the fourth stage.

Table 1. Characterized Fiber Lengths of the Cascaded Delay Line Structure (unit: mm)

Arm	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
0	0	0	0	0	0	0	0
1	358.22	1095.10	3312.06	9986.50	29903.06	89728.97	269176.03
2	742.52	2213.94	6645.21	19943.52	59816.22	179454.28	538376.25

The summation of the "2" arms in all stages results in the extended measurement range of 807,191.94 mm.

The spatial resolution of the modified fiber-optic low-coherence measurement based on the proposed multiple-stage delay line was also characterized. It is defined by the full-width at half-magnitude (FWHM, 3 dB width) of the low-coherence interference signal. Figure 6 summarizes all the characterized spatial resolution as a function of the stage order (Kth) of the delay line. The Kth stage in Fig. 6 corresponds to the measurement range when the longest "2" arms of all the first–Kth stages are connected in series. For example, the inset of Fig. 6 illustrates the magnified interference signal of the right peak in Fig. 5(a) corresponding to the third stage, which clearly shows that the spatial resolution (FWHM) is about 68 μm. It is further known from Fig. 6 that for the maximum achievable range of 0.8 km (the seventh stage used), the spatial resolution is close to about 60 μm. It is noted that the measurement uncertainty will be larger when the measurement range is extended because the measurement results are based on the accumulative measurement uncertainty for each stage.

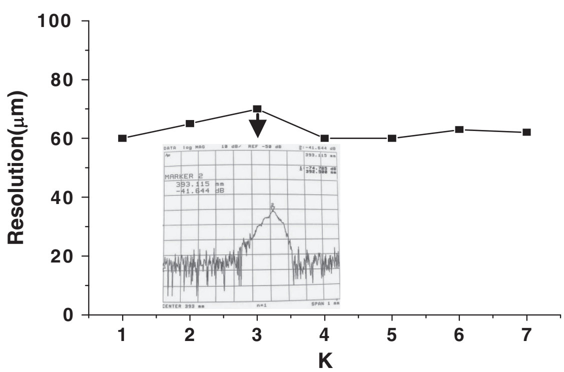

Fig. 6. Spatial resolution as a function of the stage order (Kth) of the delay line. The Kth stage corresponds to the measurement range when the "2" longest arm of all the first–Kth stages are connected in series. Inset, magnified view of the right peak in Fig. 5(a), giving the spatial resolution of 68 μm when the first–third stages are used.

In experiment, we measured the fiber length of an FUT with the length close to the extended measurement range. The seven-stage cascaded delay line is connected to the D port of the instrument, and the FUT is in series connected to the FUT_0 through the A and B ports of the instrument (see Fig. 1). The measurements include two steps. First, the FUT is not connected, and all the "0" arms of the stages are set at the "ON" state. The experimental result is shown in Fig. 7(a). Second, the FUT is connected, and all the "2" arms of the stages are set at the "ON" state. Figure 7(b) depicts the experimental result. The fiber length of the FUT is determined by the fiber lengths of the "2" arms of all stages minus the net difference between the above two measurements; that is, 807191.94 – (235.47 – 37.31) = 806993.78 mm. It is noted that the SNR is about 10 dB, which is still high enough for detection.

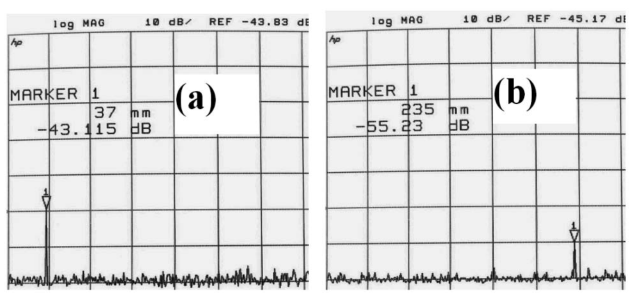

Fig. 7. Measurement results of an unknown FUT. (a) FUT is not connected to FUT_0 and the "0" arms of all stages are set at the "ON" states. (b) FUT is in series connected to FUT_0 and the "2" arms of all stages at the "ON" states.

The present work was aimed to verify the cost-effective method to extend measurement range extension with unchanged spatial resolution. All the stages of the fiber delay lines were manually switched between the status of "ON" or "OFF." The average process for multiple measurements was carried on to eliminate the measurement uncertainty. However, for the real application, a more trustworthy solution to switch all the stages should be considered, such as by the use of a low insertion loss of optical, electric-optic, or mechanical switches. On the other hand, temperature instability is an important factor that influences the accuracy of the measurements. According to an approximate estimation, the length vibration of the delay line is about 6 mm/°C for the maximum 0.8 km measurement range. It is needed to insert all the configured delay lines into a temperature controller.

4. Conclusion

We have proposed a simple method to extend the fiber-length measurement range of the fiber-optic low-coherence measurement system based on the cascaded fiber delay line structure. This method is cost-effective but ensures a great extension of the measurement range. Experimental demonstration shows that the measurement range can be extended to 0.81 km (with resolution of 60 μm), which is as large as more than 2000 times of the original one of the measurement system. Compared with the method based on the F–P resonator [5,6], our proposed method has the following advantages: first, the extension (N^k) of the measurement range can be significantly large because of the exponential nature of the cascaded fiber delay line and, second, the combinations of "ON" and "OFF" in each splitting arm of the cascaded stages can smoothly select the measurement range.

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