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High-Resolution Measurement of Fiber Length Change with Optical Low-Coherence Reflectometer Based on a Fiber-Ring Structure

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A simple approach is proposed and experimentally demonstrated to improve measurement precision of short fiber length or fiber length change with an optical low-coherence reflectometer (OLCR). A fiber-ring structure composed of a coupler and a circulator is introduced in the test arm of OLCR to virtually multiply the length of the fiber under test. By measuring the multiplied fiber length under test, the measurement precision is enhanced. A precision enhancement of 10 times is successfully achieved. © 2011 The Japan Society of Applied Physics

In many applications such as fiber sensor and fiber delay line, the fiber length or change in fiber length has to be measured with high resolution.[1–6] So far, there are a few fiber length measurement methods. The optical time domain reflectometer (OTDR)[7] is usually used to measure the fiber length with a wide range. However, its precision is low. The optical frequency domain reflectometer (OFDR)[8,9] and optical low-coherence reflectometer (OLCR)[10–12] can achieve a resolution of up to tens of μm. Besides, for higher resolution, measurement methods such as the use of mode-locked fiber laser[13] and free running[14] have been demonstrated. They are, however, usually complicated and expensive. In some circumstances, such as precision fiber delay lines, the fiber is short and its length or length change has to be characterized with a resolution of up to μm.

In this paper, we propose a simple method of enhancing the measurement precision of a short-length fiber or the fiber length change with an OLCR. A fiber-ring cavity is inserted into the test arm of the OLCR, in which light can travel for multiple trips before interfering with the light from the reference arm of the OLCR. The all-fiber-ring cavity possesses the inherent features of low insertion loss and easy implementation with low cost in comparison with other methods.

The conventional OLCR system is based on the Michelson Interferometer configuration and the light source is a broadband one, such as the amplified spontaneous emission (ASE) source. Only when the difference in optical paths between the reference and test arms is less than the coherent length of the light source, will there be a strong interference between the two signals, and the fiber length to be tested is then determined (equal to the reference arm length). By simply changing the length of the reference arm via, for example, a movable mirror, the measured position of the test arm will be scanned. The precision is in principle related to the bandwidth of the light source and the mirror scanning precision.[11]

To improve the precision of the fiber length measurement, we modified the conventional OLCR by inserting a fiber-ring structure as shown in Fig. 1. The light in the test arm passes from port 2 to port 3 of the first circulator (Cir 1), and is divided into two parts via coupler 2. One part goes back to the circulator 1 and interferes with the reference arm. The other part travels in the proposed fiber-ring cavity, which consists of two arms of coupler 2 (L_4 and L_5) and the second circulator (Cir 2). The fiber under test (FUT) is inserted between port 3 of Cir 2 and a Faraday rotator mirror (FRM) that is used as an inline reflector to improve the polarization stability. As shown in Fig. 1, the fiber-ring cavity length includes two arms of coupler 2 (L_4 and L_5) and the doubled length from port 2 of Cir 2 to the FRM, i.e., $2 \times (L_6 + L_{\mathrm{FUT}} + L_7)$. Consequently, the total length of the device under test (DUT) is determined by

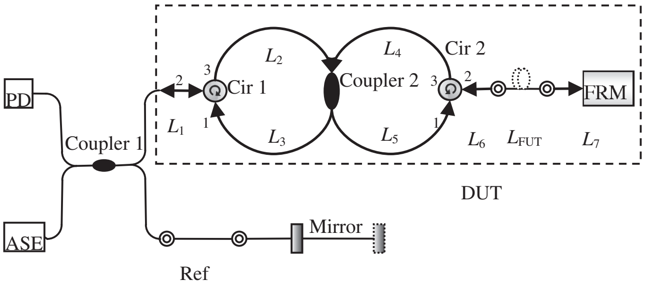

Fig. 1. Experimental setup of OLCR with the proposed fiber-ring structure (in the dashed box). PD: photodiode; DUT: device under test; Cir: circulator; FRM: Faraday rotator mirror.

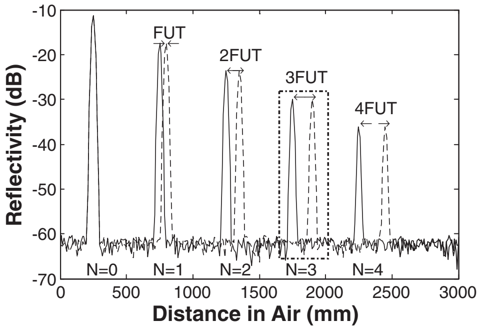

Fig. 2. Demonstration of measurement window of the OLCR when a different order of travelling circles in the ring cavity is selected.

$$L_{\mathrm{DUT}} = 2L_1 + L_2 + L_3 + N \times (L_4 + L_5 + 2L_6 + 2L_7 + 2L_{\mathrm{FUT}}), \qquad (1)$$

where N is the order of the traveling circle in the fiber-ring cavity; L_1, L_2, and L_3 correspond to the lengths of port 2, port 3, and port 1 of Cir 1, respectively.

Figure 2 illustrates a different-order measurement window of the modified OLCR when the reference arm length is set at a different value. The solid lines stand for the case without FUT, and the dotted lines denote the case with FUT. The length difference (L_{T}) between the two cases is equal to

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$N \cdot L_{\mathrm{FUT}}$, and the multiplied factor (N) can be simply estimated from the measurement window, as shown by the dash-dotted lines in Fig. 2.

In the traditional OLCR without the fiber-ring cavity inserted in the test arm, the FUT length is just given by the length difference as $L_{\mathrm{FUT}} = L_{\mathrm{T}}$. Comparably, the measurement precision based on the fiber-ring structure proposed here is enhanced by N times:

$$\frac{\delta L_{\mathrm{FUT}}}{L_{\mathrm{FUT}}} = \frac{\delta_{\mathrm{T}}}{N}, \tag{2}$$

where δL_{FUT} is the measurement error of L_{FUT}, and δ_{T} is the relative measurement error ($\delta_{\mathrm{T}} = \delta L_{\mathrm{T}}/L_{\mathrm{T}}$ with δL_{T} the measurement error) of the OLCR system.

To validate the proposed approach, we performed two experiments based on the HP 8504A Reflectometer as the OLCR, which has a measurement range, i.e., the scanned range of the movable mirror in the reference arm, of 400 mm in air ambient.

First, we configured a DUT by using a 3 dB coupler, where two ports (L_4 and L_5 in Fig. 1) were spliced together to simulate the above-mentioned fiber-ring cavity. The total length of the ring cavity is as short as 86.2 × 2 mm ($L_4 + L_5$). A proper reference fiber was selected so that four different orders of the traveling circles in the ring cavity appear simultaneously in the measurement window. The experimental result is shown in Fig. 3. The reflectivity for neighboring orders is decreased by about 5–6 dB, which is due to the insertion loss and splitting nature of the 3 dB coupler.

Next, we investigated the performance of the modified OLCR based on the proposed approach for the fiber length measurement. Except that L_{FUT} and N are variable, all the other parameters (L_{i} with $i = 1$–7) in eq. (1) are constant as long as the fiber-ring cavity consisting of coupler 2 and Cir 2 was experimentally configured. A tunable fiber delay line (FDL, made by General Photonics) with a tuning precision of 3 µm was used as the FUT. The fiber length of the FDL was precisely tuned by 1.000 mm. Examples of measurement results are illustrated in Fig. 4, where Figs. 4(a)–4(e) correspond to different orders of $N = 2$, 4, 6, 8, and 10, respectively. In Fig. 4, the left subplots [such as (a.1)] denote the results when FDL was not tuned while the right ones [such as (a.2)] represent the results when FDL was tuned at 1.000 mm. The scanned range of the movable mirror was set to be 12 mm, and the vertical scale is 10 dB/div for Figs. 4(a)–4(d) and 5 dB/div for Fig. 4(e). It is noted that the fiber length (L_{ref}) in the reference arm is approximately chosen for each order of N according to $L_{\mathrm{ref}} = L_{\mathrm{DUT}}/2$ and eq. (1). L_1, L_2, and L_3 are 55, 80, and 80 cm, respectively; L_4, L_5, L_6, L_{FDL}, and L_7 are 80, 80, 55, 230, and 110 cm, respectively.

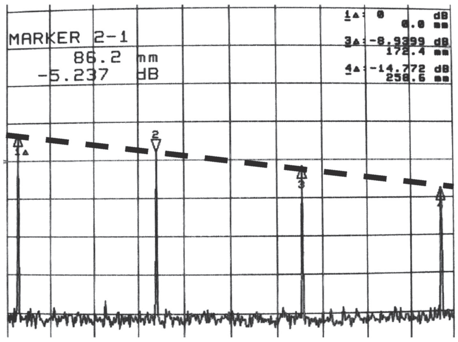

Fig. 3. Experimental validation of the measurement window of the OLCR (HP 8504A Reflectometer) when a short-length DUT without FUT was used. The vertical scale is 10 dB/div.

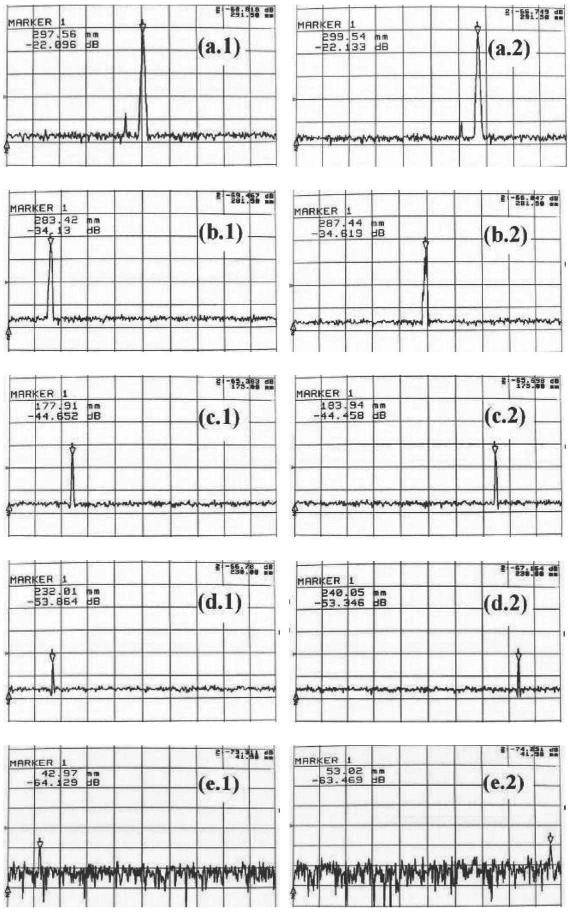

Fig. 4. Measurement results of the tuned FDL for different traveling orders (N). (a.1, 2), $N = 2$; (b.1, 2), $N = 4$; (c.1, 2), $N = 6$; (d.1, 2), $N = 8$; (e.1, 2), $N = 10$. The vertical scale is 10 dB/div for (a)–(d), and 5 dB/div for (e).

The length difference (L_{T}) of the tuned FDL was deduced from the difference between the left and right subplots in Fig. 4 [such as Fig. 4(a.1) and Fig. 4(a.2)]. To achieve the highest precision, it was experimentally performed after setting each measurement span of Fig. 4 as the minimum 1.000 mm of the OLCR (HP 8504A Reflectometer). L_{T} is 1.033, 2.028, 3.025, 4.030, 5.035, 6.035, 7.025, 8.033, 9.025, and 10.030 mm for $N = 1$ to 10, respectively. Using the equation of $L_{\mathrm{FUT}} = L_{\mathrm{T}}/N$, we can evaluate the tuned length of the FDL for different orders. The measurement error is plotted as a function of the order (N) with open squares in Fig. 5. The theoretical estimation of eq. (2) is also illustrated with solid squares in Fig. 5, which is in good agreement with the experimental result.

The reflectivity for each order (N) is summarized with open circles in Fig. 5. It is shown that the reflectivity difference between two neighboring peaks is about 6 dB, which is also due to insertion loss, polarization-dependent

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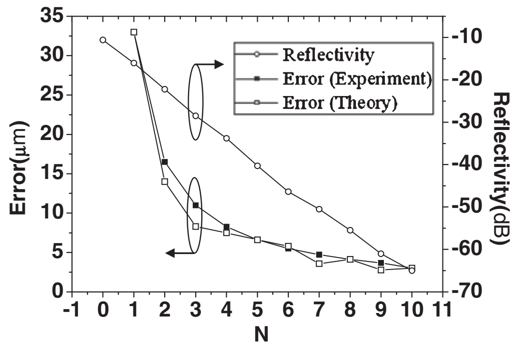

Fig. 5. Measurement error and reflectivity are plotted as functions of the order N of the traveling circles in the ring cavity of the modified OLCR.

loss of the optical components and splitting nature of the 3 dB coupler. For $N = 0$, the reflectivity is about -10 dB and the noise floor of the OLCR is about -70 dB (see Fig. 4). This is the reason why the maximum achievable improvement of the fiber length measurement is limited to 10 times.

The measurement precision of our approach (about 3 μm) is superior to other high-precision techniques and commercial instruments[15)] but at a cost of the measurement range within $400/N$ mm since the range of the movable mirror in the current experimental setup is limited to 400 mm. However, it can be expected to extend the measurement range using a fiber delay line structure.[16)]

Temperature is an important factor affecting the precision in the experiment because of its influence on the fiber length and refractive index. Since both the reference and test arms have almost the same fiber types, the influence of temperature fluctuation only originates from the length of the movable mirror (400 mm). Considering the temperature coefficient of 8×10^{-6}/°C for silica-based optical fibers,[17)] the change in the optical path difference is approximately 3.2 μm/°C, which indicates that the temperature influence is ignorable if the environmental temperature fluctuation is controlled within 10 °C.

In conclusion, we have demonstrated a simple fiber-ring structure to improve the measurement precision of fiber length with an OLCR. By setting different fiber lengths in the reference arm, we can control and select the order of the traveling circles in the fiber-ring cavity. The precision enhanced by 10 times is successfully achieved, that is, a measurement error of 30 μm can be improved to about 3 μm at the cost of the measurement range. The approach demonstrated has the following advantages: first, the fiber-ring structure is very simple and cost-effective; second, it can be applied to any other OLCRs with a wider bandwidth of the light source or higher precision. If the visibility (the noise floor as well) of the reflectometer can be further enhanced or the total loss in the ring cavity can be reduced (such as by the use of coupler 2 with 1 : 9 or 1 : 99 splitting ratio), the measurement precision will be significantly improved. It is a good method of improving the measurement precision based on the commercial OLCR at a low cost.

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