Extended-range FMCW reflectometry using an optical loop with a frequency shifter

<table>
<thead>
<tr>
<th>メタデータ</th>
<th>言語: eng</th>
</tr>
</thead>
<tbody>
<tr>
<td>出版者:</td>
<td></td>
</tr>
<tr>
<td>公開日: 2017-10-03</td>
<td></td>
</tr>
<tr>
<td>キーワード (Ja):</td>
<td></td>
</tr>
<tr>
<td>キーワード (En):</td>
<td></td>
</tr>
<tr>
<td>作成者:</td>
<td></td>
</tr>
<tr>
<td>メールアドレス:</td>
<td></td>
</tr>
<tr>
<td>所属:</td>
<td></td>
</tr>
<tr>
<td>URL</td>
<td><a href="https://doi.org/10.24517/00007400">https://doi.org/10.24517/00007400</a></td>
</tr>
</tbody>
</table>

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 3.0 International License.
Abstract—We propose a novel method to extend the measurement range of FMCW reflectometry. In this method, an optical loop with a frequency shifter (working frequency $f_{FS}$ Hz) is incorporated in the reference arm of the reflectometry. As a result, the interference signal corresponding to the reference beam that circulates $N$ rounds in the loop appears around $(N \times f_{FS})$ Hz, which means that the signals from different measurement ranges can be detected in different frequency domains. Therefore, it is possible to extend the measurement range. In the experiment, the measurement range is extended from 15 m to 48 m.

I. INTRODUCTION

FREQUENCY modulated continuous-wave (FMCW) reflectometry is a promising candidate for measuring reflection signals from fiber connectors, packaged optical devices and optical integrated devices [1]–[4]. FMCW reflectometry is mainly composed of a laser source whose optical frequency is linearly chirped in time and a two-beam interferometer shown in Fig. 1. Since the frequency of laser source is modulated by an injection current with a shape of saw-tooth wave, the interference signal between the reference beam reflected by the mirror and the signal beam from the device under test appears at the following beat frequency $f_b$:

$$f_b = 2nL f_m \Delta F/c,$$

where $n$ is the refractive index of the air, $2nL$ the optical path difference (OPD) between the reference and the signal beams, $f_m$ the repetition frequency of the injection current, $\Delta F$ the variation of frequency in chirped range of the injection current and $c$ the light velocity. Therefore, the reflection signal from the device under test can be observed by a spectral analyzer. Because the detective signal is a kind of interference signal, and the maximum of $2nL$ should be equal to the OPD corresponding to the coherence length $L_c$ of the laser source (i.e., $2nL = nL_c$, where the coherence length $L_c$ is measured in air), the maximum of measurement range $L$ is only equal to $L_c/2$.

In this letter, we propose a novel method to extend the measurement range of the FMCW reflectometry and demonstrate the validity of the method.

Manuscript received July 24, 1995; October 13, 1995.

The authors are with the Department of Electrical and Computer Engineering, Faculty of Engineering, Kanazawa University, 2-40-20 Kodatsuno, Kanazawa, 920 Japan.

Publisher Item Identifier S 1041-1135(96)00943-3.
ZHOU et al.: EXTENDED-RANGE FMCW REFLECTOMETRY USING AN OPTICAL LOOP WITH A FREQUENCY SHIFTER

Fig. 2. Proposed extended-range FMCW reflectometry.

Fig. 3. Signal power spectrum around 0 Hz for \( L = 0 \sim 1/2 \).

Fig. 4. Signal power spectrum around 85 MHz for \( L = 1/2 \sim 1 \).

Fig. 5. Signal power spectrum around 170 MHz for \( L = l \sim 3/2 \).

of the optical fiber. Then (1) becomes as follows

\[
f_b = n'(2L - N l) f_m \Delta F / c + N \times f_{FS}\]

\[ (N = 0, 1, 2, \ldots, \infty) \tag{2} \]

Because the maximum value of \( n'(2L - N l) \) is equal to the OPD related to the coherence length \( L_c \) of the laser source (i.e. \( n'(2L - N l) = n'L_c \approx n'l \)), the measurable range \( L \) is approximately extended to the \((1+N)l/2\). If \( N = 0 \), the output signals from \( L = 0 \sim 1/2 \) appear around 0 Hz; if \( N = 1 \), the signals in the range of \( L = 1/2 \sim l \) appear around \( f_{FS} \) Hz; and generally, the signals in the range of \( L = Nl/2 \sim (1+N)l/2 \) appear around \((N \times f_{FS})\) Hz. The maximum value of \( N \), or the measurable extended range \((1+N)l/2\), is mainly determined by the optical loop loss. It should be noted that the frequency modulation characteristics of laser diodes are affected by (1) the thermal response time of the laser diode, (2) the current dependence of the FM efficiency and (3) the presence of mode hopping due to an optical feedback to the laser diode [5]. Therefore, FM responses of laser diodes show frequency tuning nonlinearity when injection current is a sawtooth wave current. A direct effect of this nonlinearity on detected signals is that the output signal spectrum is broadened, and in turn, the spatial resolution and the identification of two close targets are seriously limited. As demonstrated in reference [3], a simple and effective solution to this problem is to enhance the high-frequency components in the modulation current through a frequency equalizer to improve the frequency tuning nonlinearity.

III. EXPERIMENTAL RESULTS

In the following experiments, we measure Fresnel reflections at the far end of several optical fibers using the system as shown in Fig. 2. Fig. 3 shows the signal power spectra around 0 Hz for \( L = 0 \sim 1/2 \). The reflection signals become smaller with the increase of the measurement distance, because coherence degree becomes low. The reflection signals can be detected only for \( L \leq 15 \) m. Failure to observe the signal for \( L > 15 \) m is due to the OPD \((2n'L_2)\) between two arms of the reflectometry is longer than the coherence length of the laser source. The result indicates that the measurement range of the system without the optical loop with the frequency shifter is shorter than 15 m.

The signal power spectra around 85 MHz for \( L = l/2 \sim l \) are shown in Fig. 4. A stronger reflection signal is detected at \( L = 17 \) m. The occurrence of this signal is due to OPD \((n'(2L - l))\) between two arms is shorter than the coherence length of the laser source, when the reference beam circulates one round in the optical loop. For the same reason, the reflection signals from \( L \leq 30 \) m as shown in Fig. 4 can
IV. CONCLUSION

We have proposed and demonstrated a novel method of extending the measurement range of FMCW reflectometry. In this method, an optical loop with a frequency shifter (working frequency $f_s$ Hz) is incorporated into the reference arm of the reflectometry. As a result, the interference signal corresponding to the reference beam which circulates $N$ rounds in the loop appears around $(N \times f_s)$ Hz. We can observe the signals from different range in different frequency domain. The measurement range is extended from 15 m to 48 m. The measurement range should be further extended if an optical loop with low loss is used.

REFERENCES