Extended-Range Optical Low-Coherence Reflectometry Using a Recirculating Delay Technique

Douglas M. Baney, Wayne V. Sorin
Instruments and Photonics Laboratory
HPL-93-33
April, 1993

optical low-coherence reflectometry, optical time domain reflectometry, amplified spontaneous emission, optical reflections, high resolution

We propose a novel technique allowing for a substantial increase in the distance measurement range for optical low-coherence reflectometry. By introducing a recirculating delay into the interferometer reference path, we achieve a one hundred times increase in range compared to previous optical low-coherence reflectometry techniques. At this extended range, a reflection sensitivity greater than -80 dB is demonstrated at a probe wavelength of 1.55 μm.

1 Introduction

Optical low-coherence domain reflectometry (OLCR) has proven to be very effective for the measurement of small closely-spaced optical reflections[1]. Such reflections are often encountered in optical fiber-based communications systems and can cause degraded performance. High spatial-resolution reflection measurements provide a useful tool for locating reflection sites, thus permitting corrective action. Resolutions as small as 1.9 μm have been demonstrated[2].

High-reflection sensitivity with OLCR is achieved by use of coherent detection. This has been demonstrated with a variety of low-coherence sources such as super-luminescent diodes[3] and erbium-doped fiber pumped by semiconductor lasers[4] or Ti-sapphire lasers[5], achieving -136 dB, -148 dB and -161 dB reflection sensitivities, respectively. All OLCR results reported to date are constrained to very limited measurement ranges. The scan range is determined by the distance an optical mirror in one arm of the interferometer can be physically displaced. This poses problems when an optical device to be measured has an unknown fiber pigtail length that is many times longer than the length of travel (0.2 meter) of linear stages that are commonly used. In that case, unless the location of the device reflection is known to within ~20 cm or less, permitting the appropriate reference path length adjustment, measurements with conventional OLCR setups can become tedious. The object of this letter is to propose and demonstrate a technique to extend the scan range by several orders of magnitude while achieving comparable resolution to conventional OLCR.

2 Extended-Range Technique

The optical circuit for the extended-range OLCR proposed here is shown in Fig. 1. This circuit is similar to that used in reference 4, except for the addition of a fiber Fabry-Perot (FFP) resonator and optical isolator. The fiber Fabry-Perot acts as a memory element providing delayed replicas of the original low-coherence source. Introduction of a high finesse resonator into the reference arm substantially reduces the reference arm power. However, it has been shown that for high power low-coherence sources where intensity noise dominates, reduction of the OLCR reference power is beneficial, resulting in improved receiver signal-to-noise ratios[6]. Therefore, the OLCR sensitivity will not necessarily degrade due to the optical loss of the reference path resonator.

The extended-range OLCR concept is illustrated by the system impulse response shown in Fig. 2. The device reflection is assumed to be situated at the end of a long fiber many times the scan distance of a conventional OLCR. In the reference arm, each recirculation number adds a time delay equal to an odd multiple of the first pass transit time through the resonator. As the mirror in Fig. 1 scans through delay time τ, all the impulse responses are scanned simultaneously. When the transit time of any one of the delayed source signals through the reference arm is equal to the time delay of the signal reflected from the device, the two signals will interfere coherently at the receiver. The strength of the optical reflection is determined by the magnitude of the coherent interference.

Identification of the recirculation order which interfered with the device reflection can be performed by time division or frequency division multiplexing. In time division multiplexing, the recirculation number corresponding to a particular response is determined by appropriate gating of the source signal and the reference path with fast optical switches. Frequency multiplexing can be achieved by applying a phase modulation within the fiber Fabry-Perot cavity, this results in a different net frequency shift for each recirculation. The frequency shift of any higher recirculation is related to the fundamental response by 2n-1, where n is the recirculation number. The detected interference frequency therefore indicates which recirculation order a device reflection mixes with. Both time division and frequency division multiplexing techniques have been applied successfully in multiplexed fiber sensors to query individual sensors[7,8]. In our work, frequency domain techniques were used to determine the recirculation order because of the limited availability of low-loss fast optical switches.

3 Experiment

The unpolarized amplified spontaneous emission from a 980 nm diode-pumped erbium-doped fiber produced 10 mW of optical power in single mode fiber at 1.55 μm. This low-coherence source had an autocorrelation width (FWHM) of approximately 40 μm. The polarization state controller in the reference arm was adjusted to maximize the interference signal at the receiver. Phase modulation, $\phi_1(t)$, within the Fabry-Perot resonator, was achieved by stretching the fiber cavity with a piezoelectric translator. This capability was used to help identify the distance to the device reflection. The second phase modulator, located in the reference arm, consisted of fiber wrapped around a piezoelectric cylinder. This was used to generate a serrodyne frequency shift for heterodyne detection. The fiber Fabry-Perot resonator finesse was 80. The resonator cavity length was 150 mm which corresponds to a free spectral range of 680 MHz. An optical isolator was required in the reference path to prevent the strong reflection from the Fabry-Perot resonator from creating excess noise at the receiver. The receiver consisted of two photodiodes (< 50 dB back-reflection) in a balanced arrangement followed by an amplifier and electrical spectrum analyzer. Measurements were taken in a 100 Hz electrical spectrum analyzer resolution bandwidth as the mirror was scanned at a velocity of 0.5 mm/sec. This resulted in a net measurement time of approximately 4 minutes.

An important characteristic of this technique for extended-range OLCR is that the recirculating delay can be realized in standard optical telecommunications fiber. Thus the difference in dispersion between the n^{th} order recirculation in the reference arm and the propagation in the device arm can in theory be eliminated. This would not be the case for an air-filled Fabry-Perot cavity in which unbalanced dispersion (with respect to the device arm) would result in a serious degradation of spatial resolution. To investigate the impact of dispersion, the FWHM impulse response was measured for a Fresnel reflection (R = -14.7 dB) located at the end of the device arm as the device fiber was successively cut back from an initial length of 24 meters. This is shown in Fig. 3 for recirculation numbers ranging from 1 to 160. The relatively complex curve may be due to the differences in dispersion between the fiber in the resonator cavity, the reference arm air path and the device fiber. For a 160 times range increase, the differential dispersion results in a width broadening of only a factor of 2. The resonator impulse response fell off at a rate of 0.26 dB per recirculation number as shown in Fig. 3.

The system described was used to measure reflections from a photo-receiver located at the end of a 15 meter long fiber pigtail. This length corresponds to the 100^{th} order recirculation within the resonator used in the experiment. The measurement result is shown in Fig. 4. The tested device consisted of a cleaved angled fiber, gradient index lens and windowed photodetector. The reflection from the fiber and the multiple reflections from the glass photodetector window are evident. During the measurement scan, no frequency modulation was applied to the Fabry-Perot resonator so reflections from the entire device arm are aliased into the measured response. A -80 dB reflection sensitivity is obtained here with a 100X increase in measurement range. The measurement sensitivity was limited by the combined Rayleigh backscatter from the lower recirculation numbers along the 15 meter fiber length.

The absolute fiber length was verified by positioning the translatable mirror to observe interference fringes and applying a frequency shift within the Fabry-Perot cavity. The wide-band FM spectrum of the receiver photocurrent was measured and compared to the FM spectrum of the first recirculation order, resulting in an absolute fiber length estimate within ±3 recirculation orders of the actual length. This uncertainty in recirculation number was attributed to the ambient acoustic energy in the laboratory affecting the exposed Fabry-Perot resonator. The length accuracy could be increased by acoustically shielding the resonator or by using a more accurate FM index determination method such as nulling a specific FM sideband to determine the frequency shift, and thus the recirculation number.

4 Discussion

Dispersion effects were shown not to impose a large penalty, even for a high number of recirculations, since the fiber forming the Fabry-Perot resonator cavity can have a similar propagation constant to that of the device arm. In these measurements, the sensitivity was determined by the Rayleigh backscatter from the lower recirculation orders scanning the device fiber. It is expected that by applying serrodyne frequency modulation within the fiber Fabry-Perot, and tuning the receiver to the beat frequency associated with each recirculation order, the reflection sensitivity will increase. This improvement should result since Rayleigh backscatter corresponding to other recirculation orders would not be detected. Additionally, since the resonator finesse and the source power are the primary determinants of measurement range, further increase in either of these will translate to an increase in OLCR range.

5 Conclusions

A 100X increase in scan range has been demonstrated with -80 dB reflection sensitivity by introducing a recirculating delay into an OLCR measurement circuit. At a probe wavelength of 1.55 μm, the two point spatial resolution was better than 100 μm over the entire measurement range. In our experiment, this represents over 150,000 resolvable points for a single mirror scan.

6 References

[1] R. C. Youngquist, S. Carr, D. E. N. Davies, "Optical coherence-domain reflectometry: a new optical evaluation technique," *Opt. Lett.*, vol. 12, p. 158, 1987.

[2] X. Clivaz, F. Marquis-Weible, and R. P. Salathe, "Optical low-coherence reflectometry with 1.9 μm spatial resolution", *Electron. Lett.*, vol. 28, pp. 1553, 1992.

[3] K. Takada, K. Yukimatsu, M. Kobayashi, and J. Noda, "Rayleigh backscatter measurement of single-mode fibers by low coherence optical time-domain reflectometer with 14 μm spatial resolution," *Appl. Phys. Lett.*, vol. 59, p. 143, 1991.

[4] W. V. Sorin, and D. M. Baney, "Measurement of Rayleigh backscattering at 1.55 um with a 32 um spatial resolution," *IEEE Photon. Technol. Lett.*, vol. 4, p. 374, 1992.

[5] K. Takada, T. Kitagawa, M. Shimizu, and M. Horiguchi, "High-sensitivity low coherence reflectometer using erbium-doped superfluorescent fibre source and erbium-doped power amplifier'" *Electron. Lett.*, vol 29, p. 365, 1993.

[6] W. V. Sorin, and D. M. Baney, "A simple intensity noise reduction technique for optical low-coherence reflectometry," *IEEE Photon. Technol. Lett.*, vol. 4, p. 1404, 1992.

[7] J. L. Brooks, B. Moslehi, B. Y. Kim, and H. J. Shaw, "Time-domain addressing of remote fiber-optic interferometric sensor arrays," *J. Lightwave Technol.*, vol. LT-5, p. 1014, 1987.

[8] D. T. Jong, and K. Hotate, "Frequency division multiplexing of optical fiber sensors using an optical delay loop with a frequency shifter," *Appl. Opt.*, vol. 28, p. 1289, 1989.

Figure Captions

Figure 1. Interferometer setup for extended range OLCR. PC: polarization state controller; FFP: fiber Fabry-Perot resonator.

Figure 2. System impulse response shown conceptually. f_n represents optical frequency of each delayed impulse response, τ represents the reference arm mirror scan. Scanned range to device reflection is 15 meters for illustrative purpose.

Figure 3. Experimental results of signal strength variation and measurement resolution (signal FWHM) versus the recirculation number of the fiber Fabry Perot resonator. Resonator finesse was 80.

Figure 4. Device measurement results for a 15 meter device pigtail corresponding to a resonator recirculation number of $n = 100$. SMF: single mode optical fiber.

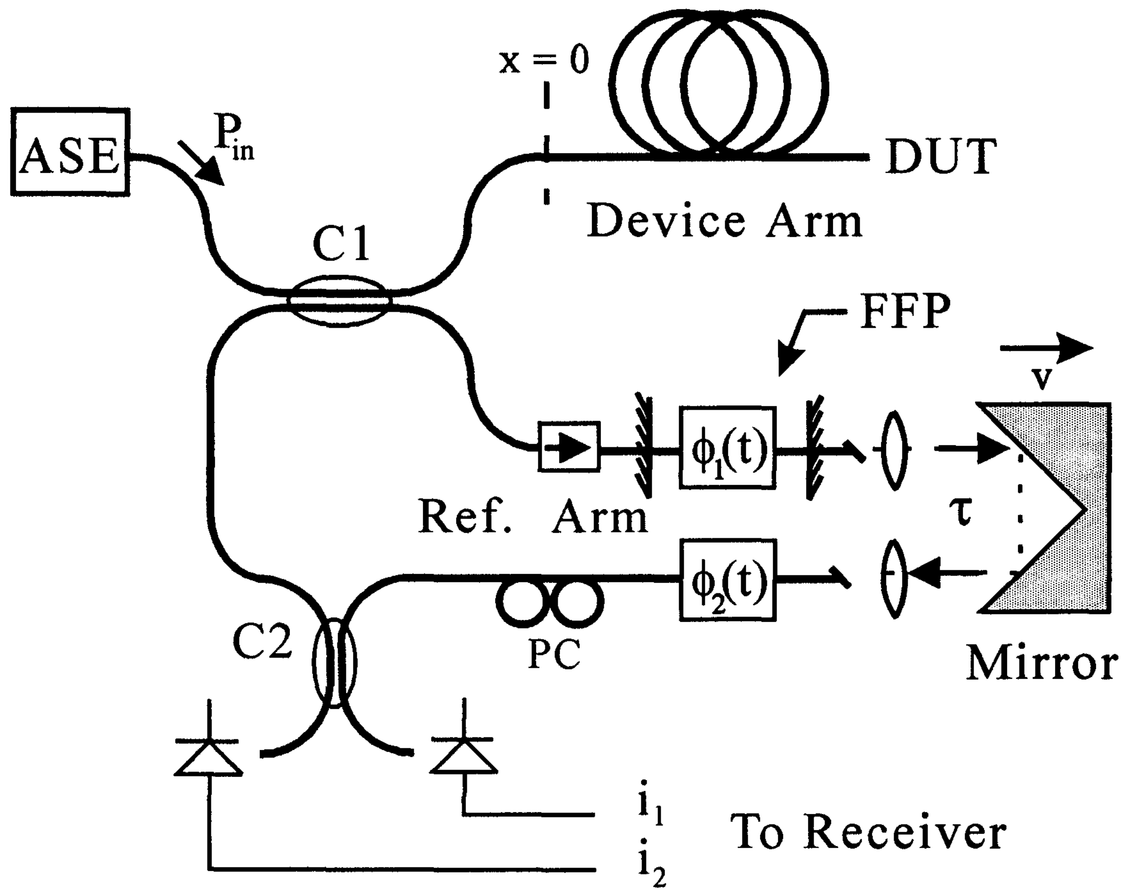
ASE
P_{in}
x = 0
DUT
Device Arm
C1
FFP
v
$\phi_1(t)$
Ref. Arm
τ
$\phi_2(t)$
C2
PC
Mirror
i_1
i_2
To Receiver

Figure 1

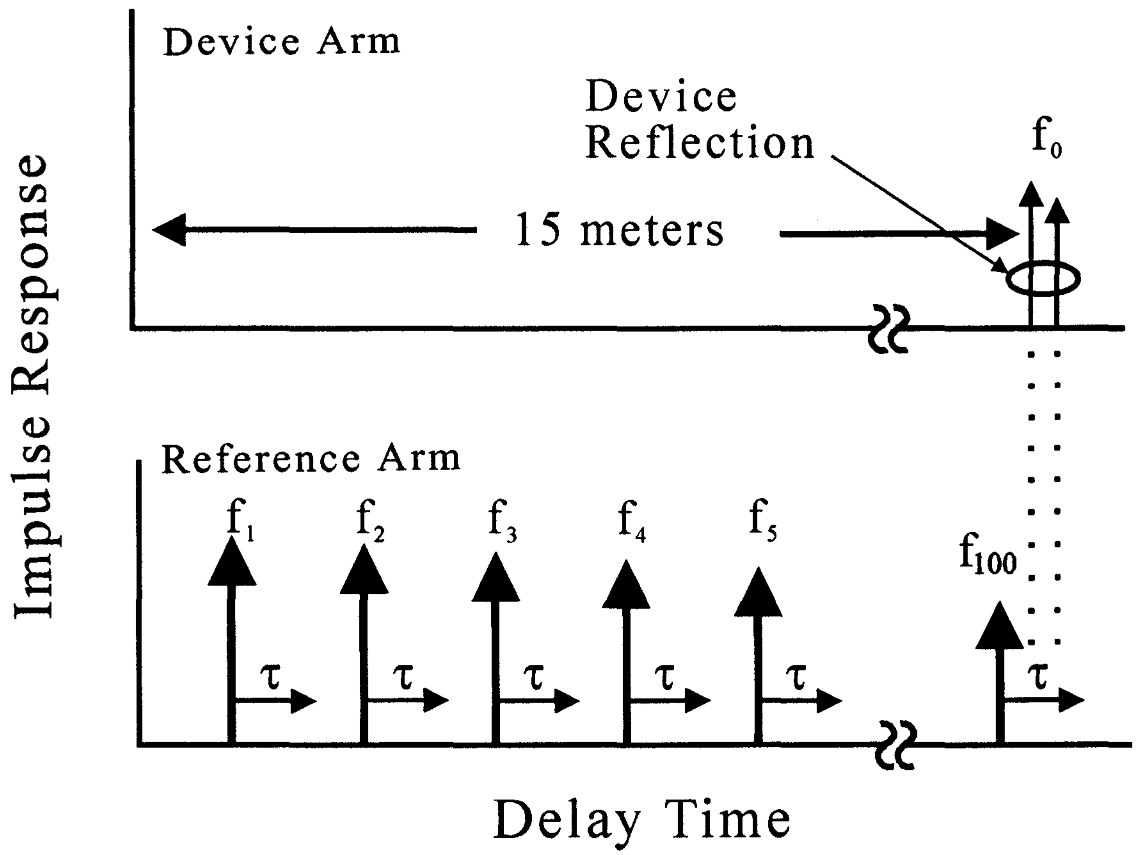
Device Arm
Device
Reflection
f_0
15 meters
Impulse Response
Reference Arm
f_1
f_2
f_3
f_4
f_5
f_{100}
τ
Delay Time

Figure 2

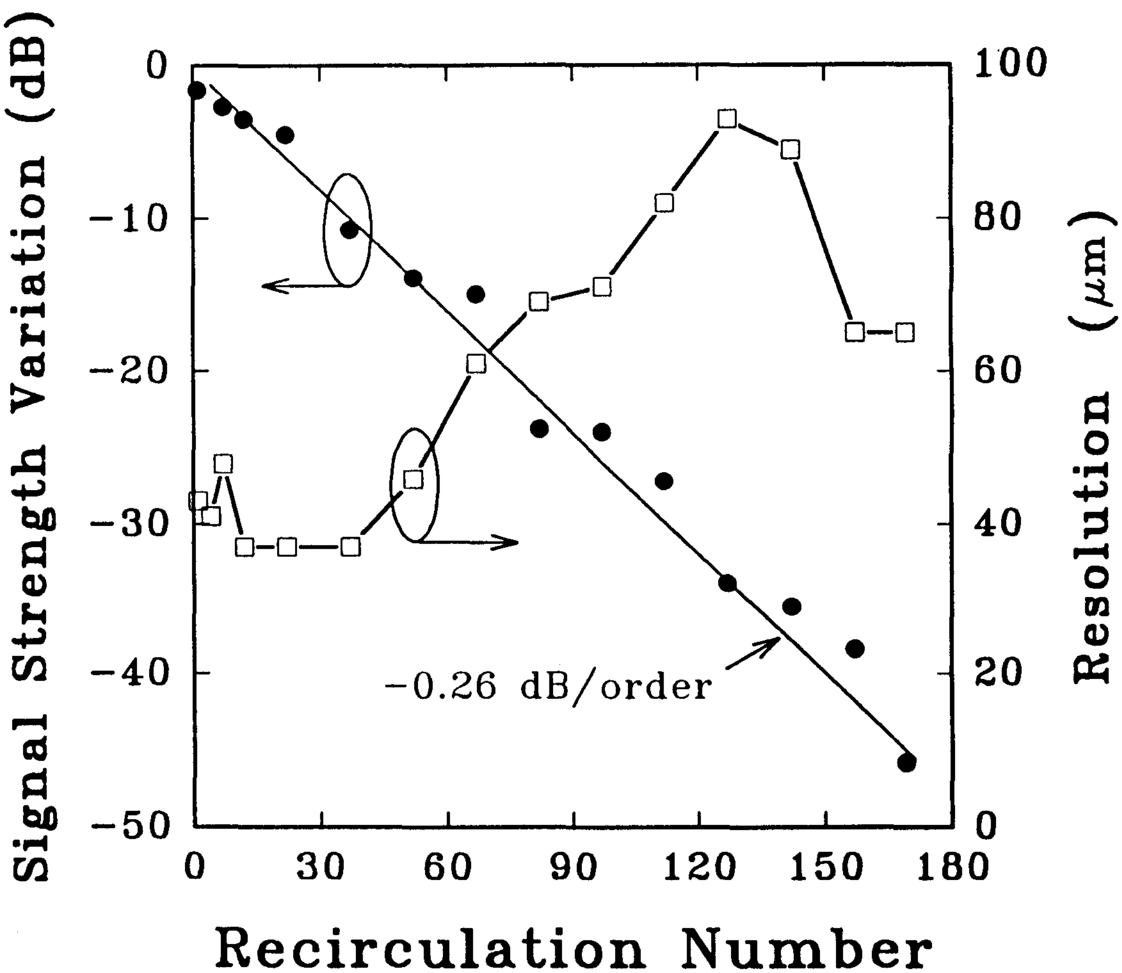
Signal Strength Variation (dB)
Resolution (μm)
Recirculation Number
−0.26 dB/order
0
−10
−20
−30
−40
−50
100
80
60
40
20
0
0
30
60
90
120
150
180

Figure 3

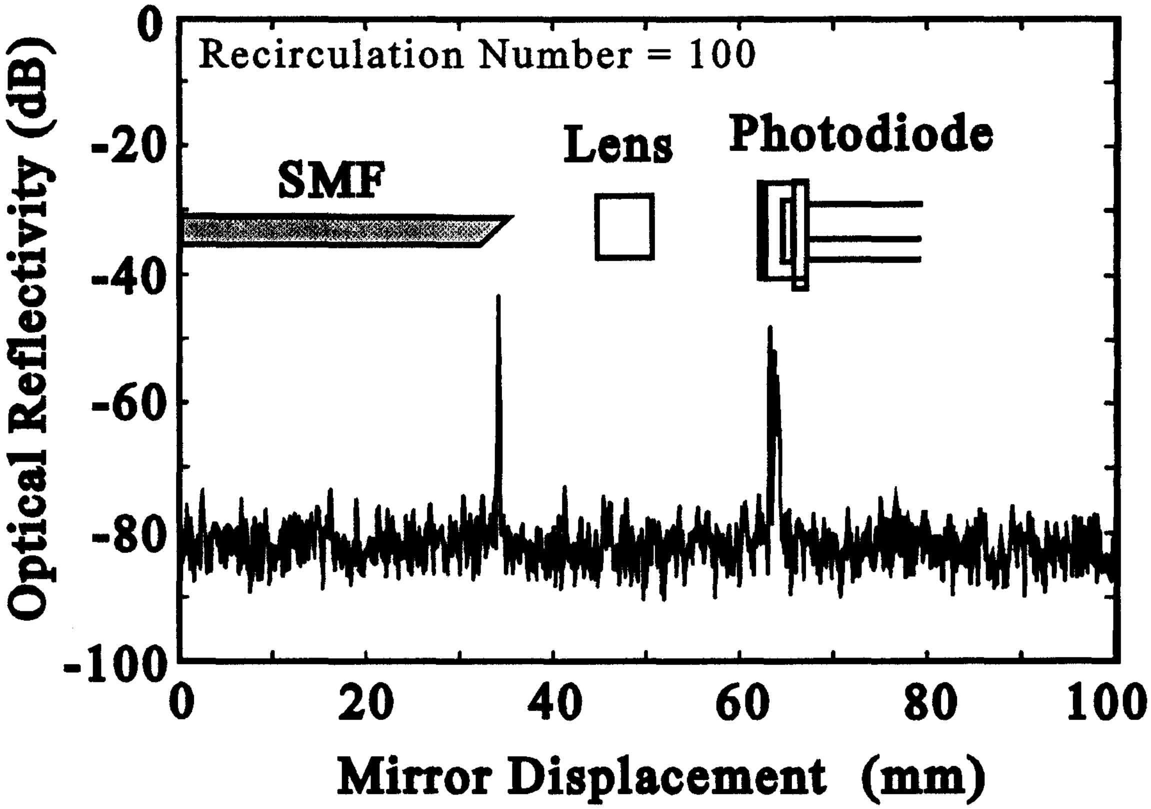
Recirculation Number = 100
SMF
Lens
Photodiode
Optical Reflectivity (dB)
0
-20
-40
-60
-80
-100
0
20
40
60
80
100
Mirror Displacement (mm)

Figure 4