

# Narrow Linewidth Fiber Laser for 100-km Optical Frequency Domain Reflectometry

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**Abstract**—A diode-pumped single-frequency piezoelectrically tuned fiber laser with narrow spectral linewidth has been used as a light source in applications for long-range coherent frequency-domain reflectometry. Frequency-modulated continuous-wave (FMCW) measurements of Rayleigh back-scattering and Fresnel reflection from a 95-km-long fiber have been demonstrated without the use of an optical amplifier. This is, to our knowledge, the longest distance measurement with FMCW. The high sensitivity and dynamic range of the long-range backscattering measurements benefit from the extremely long coherence length of the narrow linewidth fiber laser, which has been estimated to be 210 km in air.

**Index Terms**—Distance measurement, frequency modulation, laser radar, Rayleigh scattering.

## I. INTRODUCTION

LONG-HAUL optical transmission systems consist of numerous fiber spans and optical amplifiers, which have been widely deployed in both terrestrial and submarine transmission systems. Between optical amplifiers in the transmission systems, optical signals can travel for up to 120 km. Optical time-domain reflectometry (OTDR) based on backscatter measurements is currently a standard fault location technique for single-ended characterization of the fiber spans. However, most OTDR instruments commercially available using pulsed laser sources and direct detection technique have maximum measurable fiber spans of a few tens kilometers. Moreover, the OTDR technique generally has to suffer from a tradeoff between dynamic range and spatial resolution. Coherent optical frequency-domain reflectometry (OFDR) based on frequency-modulated continuous-wave (FMCW) reflectometry promises many advantages over the OTDR. It offers the possibilities of much higher sensitivity and larger dynamic range combined with higher resolution than that of the OTDR. So far, a lot of lasers have been applied to coherent OFDR applications. Laser diodes emitting around 1.55  $\mu\text{m}$  are very compact and low-cost light sources for coherent OFDR, but they have short coherence length due to their broad spectral linewidth [1]. The maximum measurable distance using laser diodes is limited to hundreds meters. Single-frequency diode-pumped solid-state lasers based on  $\text{Nd}^{3+}$  ion at 1.06  $\mu\text{m}$  and 1.32  $\mu\text{m}$  [2], or  $\text{Ho}^{3+}$ ,  $\text{Tm}^{3+}$  ions at 2.0  $\mu\text{m}$  are highly coherent light sources with narrower linewidth ( $\sim 10$  kHz) and longer coherence length

than laser diodes, which can significantly extend the measuring range. But transmission wavelengths at around 1.55  $\mu\text{m}$  are not available in these bulky crystal-based solid-state lasers. In addition, these bulk solid-state lasers contain bulk mirrors or other components in a free-space cavity and suffer from poor environmental stability and operation reliability, as well as difficult thermal management.

Recently, much attention has been given to the development of diode-pumped single-frequency fiber lasers because these lasers not only provide alternative highly coherent light sources (even with longer coherence length than that of the well-known diode-pumped monolithic nonplanar Nd:YAG ring oscillator (NPRO) lasers [3]), but they also offer multiple broad wavelength regions at 1, 1.5, and 2  $\mu\text{m}$  [4]–[6] and many unique advantages over other solid-state lasers in terms of reliability, ruggedness, and compactness. The multiple broad operating ranges of fiber lasers provide the flexibility for those remote-sensing applications where operation wavelength is vital. Recently [7], a single-frequency fiber laser with coherence length of 3.3 km has been demonstrated for use in coherent OFDR, although the demonstrated measurement range was less than 1 km. In this letter, we report to use a compact piezoelectrically tuned narrow linewidth fiber laser for long-range OFDR. Coherent FMCW measurements of Rayleigh backscattering and the Fresnel reflection from a 95-km-long fiber, which is the longest fiber available in our lab, are demonstrated. This is, to our knowledge, the longest distance measurement with FMCW. The extremely high sensitivity and dynamic range of the long distance FMCW measurements are due to the long coherence length of the narrow linewidth fiber laser, which has been characterized by self-homodyne and heterodyne techniques.

## II. NARROW LINEWIDTH FIBER LASER

The laser source is a diode-pumped single-frequency fiber laser (Scorpion, NP Photonics), which can use Yb-doped or Er/Yb co-doped fiber for wavelength operation at either 1 or 1.55  $\mu\text{m}$ . The fiber laser design was described previously [4], [5]. However, a latest improvement in noise reduction, including a more careful package design to remove vibration or acoustic noise, allows us to further reduce the laser linewidth to about 1 kHz. Since telecommunication fiber (SMF-28) is readily available in long length, we used an Er/Yb-doped fiber laser with 20 mW output power at 1555.5 nm. Figs. 1 and 2 show the results of delayed self-homodyne and heterodyne measurements of the laser using different lengths of fiber delay. The power spectra of both homodyne and heterodyne interferometric signals show clear interference fringes up to the longest delay length used in these experiments, indicating

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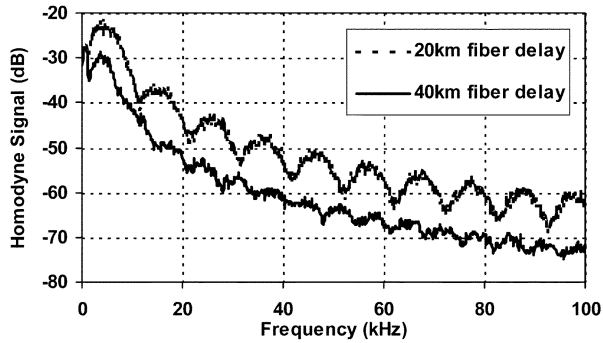


Fig. 1. Delayed self-homodyne spectra of the fiber laser with different lengths of fiber delay.

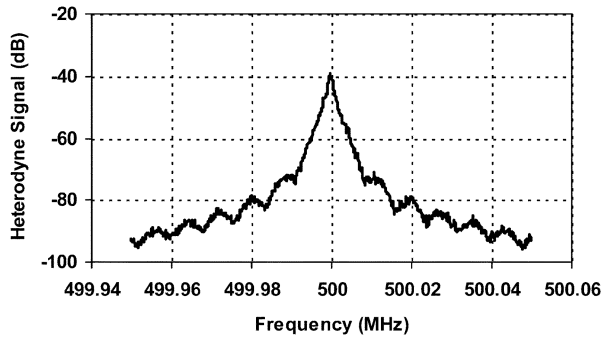


Fig. 2. Delayed self-heterodyne spectra of the fiber laser with 25-km fiber delay.

that the coherence length is considerably longer than 40 km in fiber. The modulation frequency is inversely proportional to the fiber delay length. It is the long coherence length of the laser that allows us to perform long-range coherent FMCW measurements.

The frequency of the fiber laser can be modulated through a small piezoelectric transducer (PZT) actuator, which expands or contracts the laser resonator in response to an applied voltage. Fig. 3 shows the tuning response of the laser as a function of the modulation frequency with a 1-V sinusoidal input. The PZT actuator allows a laser frequency tuning of about 27 MHz/V with a modulation bandwidth of 10 kHz.

### III. FMCW REFLECTOMETRY

The FMCW reflectometry setup is shown in Fig. 4. The fiber laser frequency is linearly chirped over 380 MHz by applying a 14-V triangular voltage at a repetition of 50 Hz to the PZT actuator. A modified fiber-based Michelson interferometer was used to detect the coherent beat signal. The short arm of the interferometer, in which the laser beam is reflected by a Faraday rotating mirror (FRM), serves as the reference beam. In the long arm, five spools of commercial single-mode fiber (Corning SMF-28) with a total fiber length of 95 km were connected in series using FC/APC connectors. This arm of the interferometer is terminated by either a FC/APC connector, or a cleaved fiber end with 4% Fresnel reflectivity. In order to prevent the generation of stimulated Brillouin scattering in the long sensing fiber, the fiber laser was attenuated to about 1 mW. The Rayleigh backscattering light from the long fiber and the Fresnel reflection at the far end were optically mixed with the reference beam

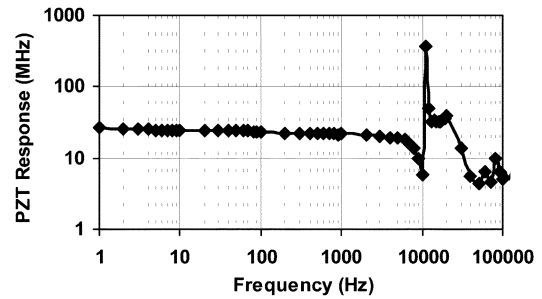


Fig. 3. PZT tuning response of the fiber laser as a function of the applied frequency with a sinusoidal input of 1 V.

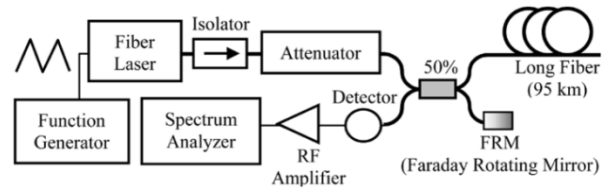


Fig. 4. Experimental setup for FMCW measurement.

and detected by a combination of a fast photodiode (Thorlabs, D400FC) and a 30-dB gain RF amplifier. No optical amplifier was necessary.

An electrical spectrum analyzer was used to record the FMCW beat signal. To avoid nonlinearities in the laser frequency tuning, the time duration of laser frequency chirp was chosen to be longer than the sweep time of the spectrum analyzer of 5 ms. The FMCW signal was recorded during the first half cycle (10-ms up ramp) of the triangular modulation, which is longer than the sweep time of the spectrum analyzer. With a PZT tuning efficiency of 27 MHz/V, the 14-V triangular voltage generates approximately 380 MHz of laser frequency tuning during the 10-ms period. Fig. 5 shows the Rayleigh-backscattered signal from the 95-km-long fiber terminated either (a) with an FC/APC connector or with (b) Fresnel reflection ( $\sim 4\%$ ) at the far end of the long fiber. The 95-km fiber used in this experiment was the longest fiber available in our lab at the moment. The first peak at around 1 MHz is due to the laser relaxation oscillation as no relative intensity noise suppression circuit was used in these experiments. After implementing a proper noise suppression circuit that is based on negative feedback to the pump laser diode, the relaxation oscillation peak could be suppressed by more than 20 dB [5], [8].

It should be noted that the spectra in Fig. 5 were obtained with an illuminating power of only about 1 mW and a reference beam power of about 0.5 mW. The optical power measured at the far end of 95-km fiber was 10- $\mu$ W. The 4% Fresnel reflection of the 10- $\mu$ W optical power (the return optical power reaching the detector is estimated at about 1 nW or  $-60$  dBm) resulted in a strong beat signal at 36 MHz with 20-dB SNR, as shown in Fig. 5(b). These results indicate that the fiber-laser-based FMCW reflectometer is able to detect signals as weak as  $-80$  dBm without using an optical amplifier. An even higher sensitivity can be expected by optimizing the use of coherent detection.

As mentioned above, the interference fringes in both homodyne and heterodyne spectra indicate that the laser coherence

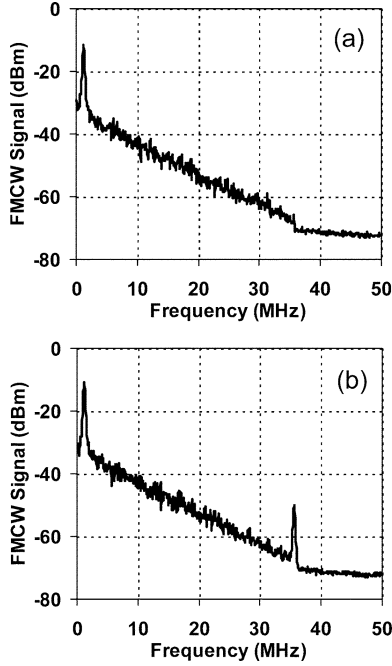


Fig. 5. Rayleigh backscattering and far-end Fresnel reflection from 95-km optical fiber were shown in (a) and (b), respectively. The 1-MHz peak comes from laser relaxation oscillation.

length is much longer than the length of fiber delay used. However, an accurate determination of the coherence length is difficult because we found a large deviation from a Lorentzian lineshape for both measurements, indicating that the laser frequency noise is not uniformly “white”[9]. This lineshape deviation is attributed to a frequency-dependent frequency noise or  $1/f$  noise of the laser. For our fiber laser, it exhibits a  $(1/f)^{0.7}$  dependence of frequency noise.

We can estimate the coherence length of the fiber laser from the decay rate of the Rayleigh backscattering signal shown in Fig. 5. In the simplest case, the power spectral density in a coherent FMCW experiment can be described by [9], [10]

$$\begin{aligned}
 S(f, \tau_d) = & (I_1 + I_2 R)^2 \delta(f) + 2I_1 I_2 R \cdot e^{-(\tau_d/\tau_c)} \delta(f - f_b) \\
 & + \frac{2I_1 I_2 R \tau_c}{1 + \pi^2 \tau_c^2 (f - f_b)^2} \\
 & \cdot \left\{ 1 - e^{-(\tau_d/\tau_c)} \cdot \left[ \cos 2\pi(f - f_b)\tau_d \right. \right. \\
 & \left. \left. + \frac{\sin 2\pi(f - f_b)\tau_d}{2\pi(f - f_b)\tau_c} \right] \right\} \quad (1)
 \end{aligned}$$

where  $I_1$  and  $I_2$  are the intensities of the reference and illumination beam and  $R$  is the reflectivity of Rayleigh backscattering or the Fresnel reflection from the long fiber. Only the second term in (1) dominates the FMCW beat signal. It is a delta function at the beat frequency  $f_b$ , weighted by a factor that includes the intensities of the two beams and an exponential function containing the ratio of the delay  $\tau_d$  to the laser coherence time  $\tau_c$ . When attenuation due to Rayleigh scattering in the fiber is taken

into account, the exponential decay of the FMCW signal in the fiber is given by

$$\frac{S(\tau_d)}{S(0)} = \exp\left(\frac{-\alpha_s c \tau_d}{n}\right) \cdot \exp\left(\frac{-\tau_d}{\tau_c}\right) \quad (2)$$

where  $\alpha_s$  is the scattering attenuation coefficient in fiber (0.039/km or 0.17 dB/km). Since the delay rate of the Rayleigh backscattering signal can be measured directly from Fig. 5 (approximately 0.4 dB/km), the coherence length of the fiber laser can be derived to be 210 km in air.

When the sensing distance is shorter than the laser coherence length, the spectral width of the beat signal is theoretically a delta function, which potentially allows an extremely high range resolution in a distance measurement. In our current FMCW setup, the range resolution was limited by the measured spectral resolution of the electrical spectrum analyzer (300 kHz at the 5-ms sweeping speed). Practically, there is a contradiction between resolution bandwidth and the sweeping speed of an electrical spectrum analyzer. This problem can be overcome in the future by using time-domain data acquisition and fast Fourier transform algorithms, instead of direct frequency-domain data acquisition with an electrical spectrum analyzer.

#### IV. CONCLUSION

We have demonstrated a compact 100-km FMCW fiber laser transmitter based on a piezoelectrically tuned narrow-linewidth fiber laser. The high sensitivity and dynamic range of the long-range backscatter measurements are the result of the extremely long coherence length of the laser, which has been estimated to be 210 km in air.

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