Linearizing optical frequency-sweep of a laser diode for FMCW reflectometry

Linearizing Optical Frequency-Sweep of a Laser Diode for FMCW Reflectometry

Koichi Iiyama, Lu-Tang Wang, and Ken-ichi Hayashi, *Member, IEEE*

***Abstract*— We propose and demonstrate a novel linearizing method of optical frequency-sweep of a laser diode for frequency-modulated continuous-wave (FMCW) reflectometry. In order to linearly sweep the optical frequency, we adopt a reference interferometer and an electric phase comparator. The interference beat signal of the reference interferometer is phase-compared with an external reference rectangular signal having a fixed frequency near the interference beat signal frequency by a lock-in amplifier. The error signal from the lock-in amplifier is fed back to the modulating signal of the injection current of the laser. Thus, a phase-locked loop composed of optical and electric circuits can be established, and the beat signal frequency is locked to the frequency of the reference signal. The optical frequency of the laser diode is, therefore, excellently linearly swept in time. In order to experimentally confirm the linearity of the proposed method, we apply this frequency-swept laser diode to the FMCW reflectometry. Resultingly, the improvement of the linearity is estimated to be about 10 dB. And the theoretically limited spatial resolution of the FMCW reflectometry is achieved. The backscattered light in optical waveguide devices is measured by the FMCW reflectometry using the proposed light source, and the propagation loss of a single-mode glass waveguide is successfully evaluated.**

I. Introduction

WITH the development of optical channel waveguide devices, there has been increasing necessity of diagnosing these devices. Although optical time domain reflectometry (OTDR) is widely used for diagnosing optical fibers, this can not be applied to optical channel waveguide devices because of relatively low spatial resolution of several tens of centimeter. Recently, low coherence reflectometry [1]–[3] composed of a low coherent light source and a two-beam interferometer is developed with sufficient high spatial resolution. In this reflectometry, the location of the surveying point within the device under test is replaced with the optical path difference of the interferometer, in which the length of the reference arm is mechanically varied by a movable stage. Although a high spatial resolution of several tens of micrometer can be easily achieved by using a superluminescent diode or an amplified spontaneous emission from an erbium-doped fiber as a light source, the practical measurement accuracy is mainly determined by the mechanical stability of the movable stage. More recently, frequency-modulated continuous-wave (FMCW) reflectometry is successfully developed [4]–[8], in which any mechanically moving component is eliminated, and stable and simple measurements can be carried out. The FMCW reflectometry is composed of a frequency-swept light source and an unbalanced two-beam interferometer with a fixed reference length as shown in Fig. 1. The backscattered light from a surveying point within the device under test interferes with the reference beam on a photodetector, and the interference signal has a beat frequency corresponding to the optical path difference. Then the optical property distribution along the device under test is mapped in the frequency domain. The spatial resolution δz is approximately given as

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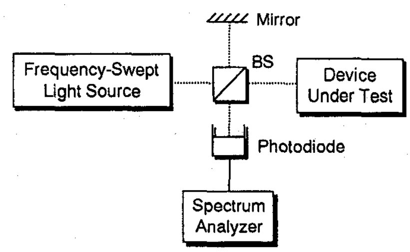

Fig. 1. Basic configuration of FMCW reflectometry.

$$\delta z = \frac{c}{2n\Delta f} \tag{1}$$

where c is the speed of light in vacuum, n is the refractive index of the device under test, and Δf is the maximum optical frequency deviation of the light source. For example, $\delta z = 1$ mm for $\Delta f = 100$ GHz and $n = 1.5$. The maximum measurable length is determined by the coherence length of the light source.

A laser diode is often used as the frequency-swept light source owing to its easy frequency modulation characteristics. The frequency modulation response of a laser diode is, in general, nonuniform against the modulation frequency, and therefore, the linear optical frequency-sweep cannot be achieved by only linearly modulating the injection current. As a result, the spatial resolution of the FMCW reflectometry is degraded.

In this paper, we propose and demonstrate a novel linearizing method of optical frequency-sweep of a laser diode for FMCW reflectometry [9], [10]. In order to linearly sweep the optical frequency, we adopt a simple reference interferometer made of a piece of single-mode optical fiber and an electric phase comparator. Establishing a phase-locked

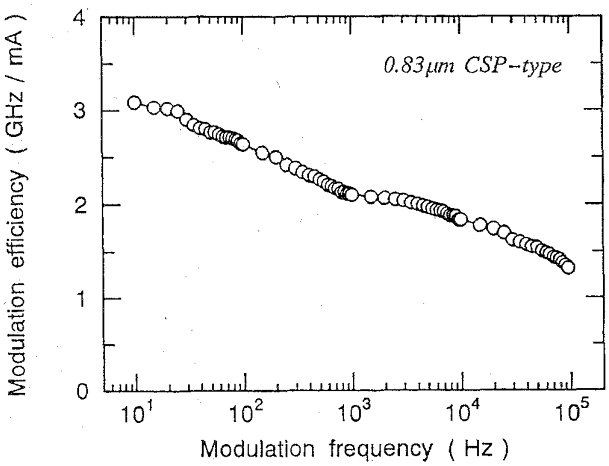

Fig. 2. Measured small signal frequency modulation efficiency of a 0.83 μm CSP-type laser diode.

loop composed of optical and electric circuits, we can excellently linearize the optical frequency-sweep in time. In order to experimentally confirm the performance of the proposed method, we apply this frequency-swept laser diode to the FMCW reflectometry. Resultingly, the improvement of the linearity is estimated to be about 10 dB. And the theoretically limited spatial resolution of the FMCW reflectometry is achieved. We also measure the backscattered light in optical waveguide devices by the FMCW reflectometry using the proposed frequency-swept laser diode and successfully evaluate the propagation loss of a single-mode glass waveguide. The proposed linearly frequency-swept laser diode is applicable as a light source not only for the FMCW reflectometry but also for the frequency-division multiplexed sensor system [11].

II. Linearizing Scheme

A. System Configuration

The frequency modulation response of a laser diode is, in general, nonuniform, and consequently, the optical frequency cannot vary with the change of the injection current, except for a sinusoidal modulation case. The measured small signal frequency modulation efficiency of a 0.83 μm CSP-type laser diode is shown in Fig. 2. In the measurement, the laser was temperature-controlled at 18°C and was operated at a bias current of 120 mA (53 mA threshold current). It is found that the frequency modulation efficiency decreases with increasing the modulation frequency. This is due to thermal effect of the refractive index of a laser diode [12]. If such a laser diode is used as the light source in the FMCW reflectometry, the beat spectrum of the interference signal spreads out and the spatial resolution is degraded.

We control the optical frequency by using a phase-locked loop composed of optical and electric circuits as shown in Fig. 3. A part of the output of a laser diode is launched into the reference interferometer made of a piece of single-mode

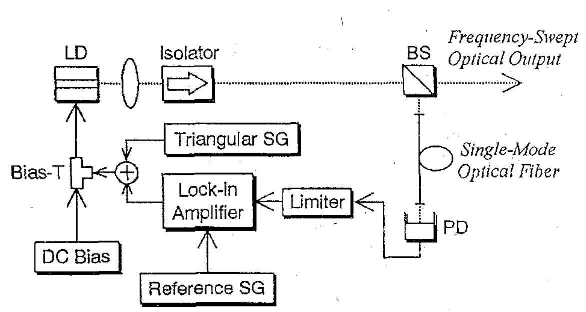

Fig. 3. Proposed system to achieve excellent linear optical frequency-sweep.

optical fiber. In the fiber interferometer, interfering beams are the beam directly emerged from the fiber and the beam reflected at the both facets of it. Multiple-reflected beams is negligible because of a low facet reflectivity of the fiber (normally 4% in power). The fiber interferometer is very suitable for the reference interferometer, since it can be easily constructed and is stable against environmental perturbations because the interfering beams propagate the same path of the fiber. The interference beat signal at the photodetector (PD) has a fixed frequency corresponding to the delay time of the interferometer if the optical frequency has perfect linear dependence on time. As mentioned above, it is difficult to achieve this condition in a laser diode when the injection current of the laser diode is modulated by a sawtooth or a triangular waveform.

Now, in order to achieve perfect linear dependence of optical frequency on time, the interference beat signal is limited in amplitude and is phase-compared with an external reference rectangular signal having a fixed frequency near the interference beat signal frequency by a lock-in amplifier. The error signal from the lock-in amplifier is fed back to the injection current of the laser diode and correct the original modulating injection current. Thus, the optical frequency of the laser diode can be rigorously linearly swept. Note that this technique is independent of the modulation characteristic of a laser diode used.

B. Experimental Results

We set up the configuration shown in Fig. 3. The laser diode used was a 0.83 μm CSP-type operating at a bias current of 120 mA (53 mA threshold current). The injection current of the laser diode was modulated by a triangular waveform with a 30 mA current excursion and a 50 Hz repetition frequency as shown in Fig. 4(a). In this condition, no mode-hopping of lasing mode of the laser diode occurs, and the maximum optical frequency deviation Δf is about 100 GHz, although a large intensity modulation is simultaneously yielded. The intensity modulation component causes sidebands in the beat spectrum and, as a result, deteriorates the spatial resolution of the system. The intensity modulation component can be eliminated by regulating the optical intensity by using an external intensity modulator or, on application side, dividing the detected signal by the optical intensity change by using a divider IC. The length of the reference fiber interferom-

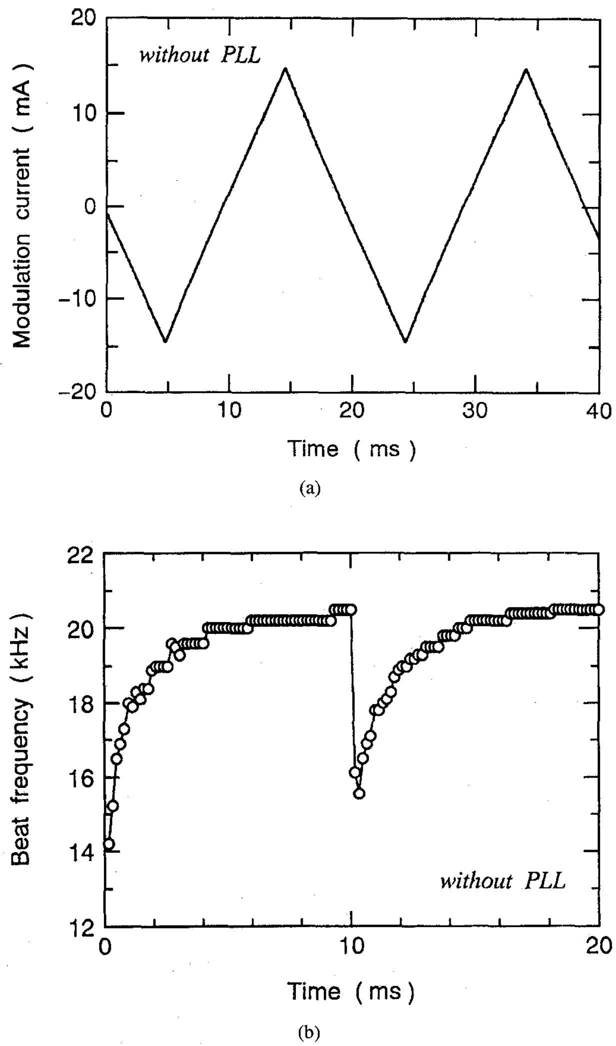

Fig. 4. Modulating triangular waveform and measured instantaneous beat frequency without the phase-locked loop. (a) Modulating triangular waveform. (b) Measured instantaneous beat frequency.

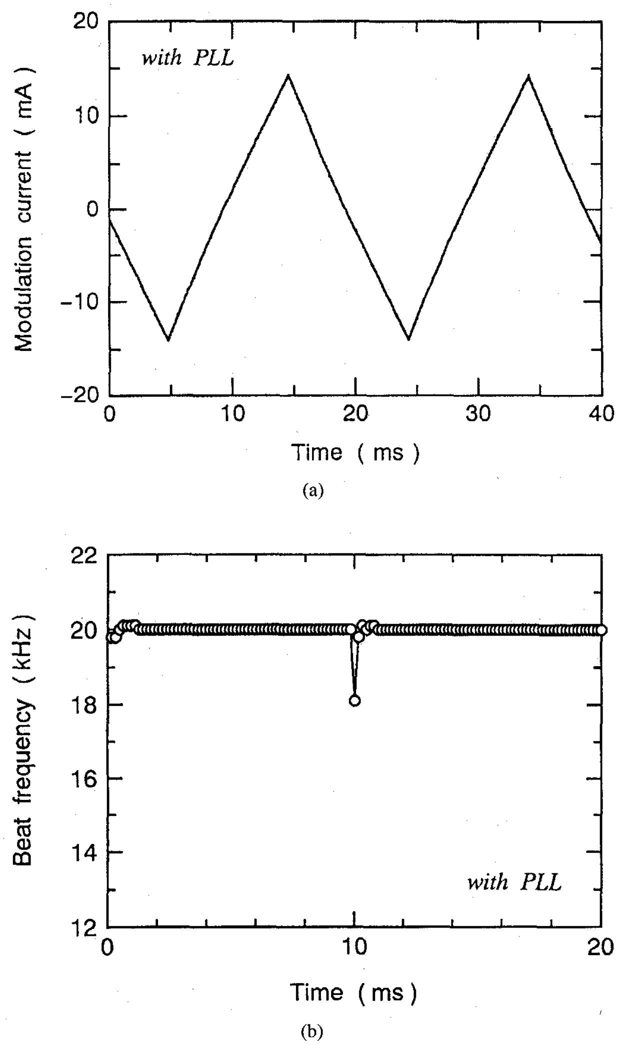

Fig. 5. Modulating triangular waveform and measured instantaneous beat frequency with the phase-locked loop. (a) Modulating triangular waveform. (b) Measured instantaneous beat frequency.

eter used was 20 cm, which generated about 20 kHz beat frequency. Fig. 4(b) shows the measured instantaneous beat frequency without the phase-locked loop. The abrupt changes of the beat frequency at 0 and 10 ms correspond to the turning points of the modulating triangular waveform. The beat frequency is not constant because of the nonlinear optical frequency-sweep.

Then, we closed the phase-locked loop of the system. The beat signal was phase-compared with a 20 kHz rectangular reference signal by the lock-in amplifier, and the resultant error signal was fed back to the injection current of the laser diode. The time constant of the lock-in amplifier was 10 ms. The corrected modulating waveform is shown in Fig. 5(a). It is found that the slopes of the triangular waveform are slightly curved. The instantaneous beat frequency was also measured and the result is shown in Fig. 5(b). The beat frequency is locked to the frequency of the reference signal. The unlocked beat frequency around the turning points of the modulating waveform is attributed to the delay time of the phase-locked loop.

III. Application to FMCW Reflectometry

In order to confirm the performance of the proposed frequency-swept laser diode, we applied it to the FMCW reflectometry. The experimental setup of the reflectometry is shown in Fig. 6, in which a balanced photo-detection scheme was adopted so as to increase the signal-to-noise ratio of the beat signal. In the following experiments, the maximum optical frequency deviation was chosen as $\Delta f = 100$ GHz, and no mode-hopping of lasing mode of the laser diode occurred. First, we chose a mirror as the device under test in order to experimentally estimate the spatial resolution of the system. Fig. 7(a) shows the measured beat signal spectrum without the proposed phase-locked loop. The spectrum spreads out and the mirror position blurs due to the nonlinear optical

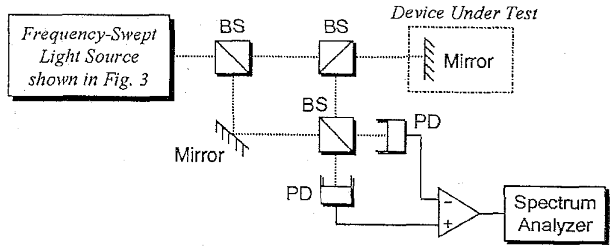

Fig. 6. Experimental setup of the FMCW reflectometry to confirm the performance of the proposed frequency-swept laser diode.

frequency-sweep, and its spatial resolution is about 12 mm. Fig. 7(b) shows the measured beat signal spectrum with the phase-locked loop. It is found that the spectrum becomes fine and the mirror position can be clearly recognized. The spatial resolution of Fig. 7(b) is 1.3 mm which is the theoretical limitation for $\Delta f = 100$ GHz and $n = 1$. Thus, we can say that the improvement of the linearity of the optical frequency-sweep is estimated to be about 10 dB.

Next we measured the Rayleigh backscattering along a single-mode optical fiber at a 0.83 μm wavelength region. The fiber length was 45 cm, and the far end of the fiber was immersed in an index matching fluid. Figure 8 shows the measured distribution of the backscatter near the far end of the fiber. The reflectivity scale is calibrated to a perfect reflection. The reflectivity of -60 dB at 45 cm is the reflection of the far end of the fiber caused by residual index mismatch. The Rayleigh backscattering along the fiber is also clearly observed and its reflectivity is about -85 dB. The amplitude uncertainty is due to coherent fading. The dynamic range of this system is determined from the noise floor to be -100 dB.

Fig. 9 shows the measured Rayleigh backscattering in a single-mode optical fiber at a 0.83 μm wavelength region. The decreasing slope of the backscattered light is clearly observed. This decreasing slope, which is read to be 0.03 dB/cm, is not due to the propagation loss of the optical fiber but is due to the optical coherence of the laser diode, since the propagation loss of the optical fiber is of the order of 1 dB/km $=10^{-5}$ dB/cm.

The contribution of the optical coherence of the laser diode on the detected signal is estimated as follows. If the laser diode has a Lorentzian spectral distribution with the spectral linewidth of $\Delta\nu$, the contribution of the optical coherence of the laser diode, $\gamma(\tau)$, for this system is given as

$$\gamma(\tau) = \exp(-4\pi n L \Delta\nu / c) \tag{2}$$

where n and L are the refractive index and the length of the device under test, respectively. In this experiment, $n = 1.5$ because the device under test is a single-mode optical fiber. From (2), the decreasing slope of 0.03 dB/cm is obtained when $\Delta\nu = 8.5$ MHz, which is a typical value for the laser diode used in our experiment.

Finally, we measured the backscattered light along an optical waveguide, and the result is shown in Fig. 10. The waveguide used was a potassium-ion-exchanged single-mode glass waveguide with single-mode optical fiber pigtails, which was fabricated in our laboratory. In the experiment, reflections

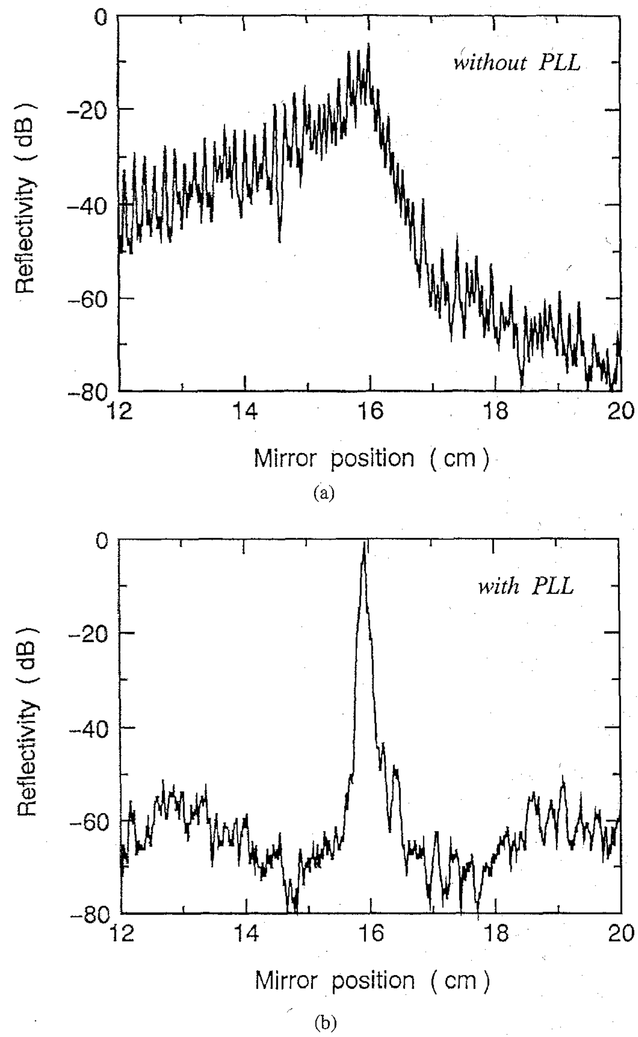

Fig. 7. Measured beat signal spectrum for the experimental setup shown in Fig. 6. (a) Without the phase-locked loop. (b) With the phase-locked loop.

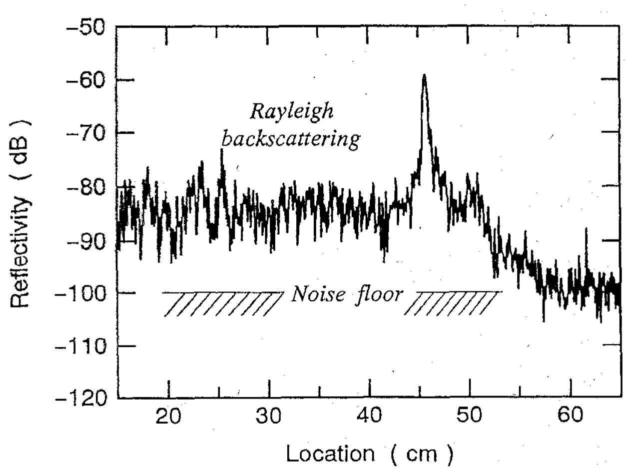

Fig. 8. Measured distribution of Rayleigh backscattering and Fresnel reflection near the far end of a single mode optical fiber.

at input and output connections of the waveguide are timely masked by an optical shutter and are not measured. The low

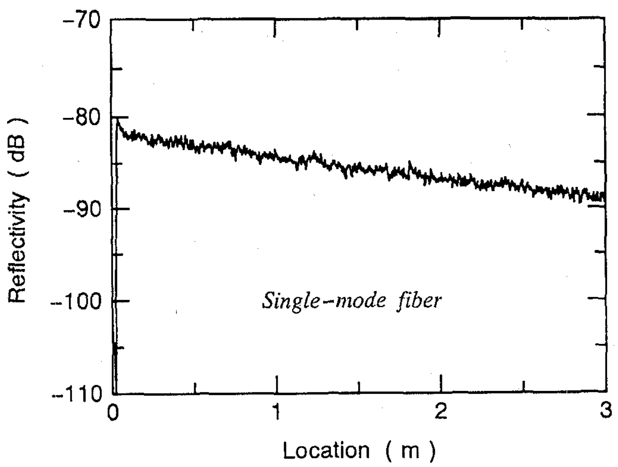

Fig. 9. Measured Rayleigh backscattered light in a single-mode optical fiber.

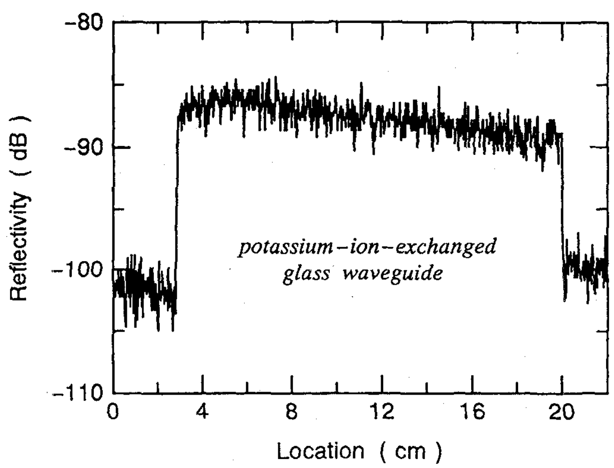

Fig. 10. Measured backscattered light in a potassium-ion-exchanged single-mode glass waveguide.

sensitivity of the backscattered light signal is attributed to large coupling loss between the optical waveguide and the input fiber. The propagation loss along the optical waveguide itself can be evaluated from the slope of this figure to be about 1.0 dB/cm after taking account of the contribution of the coherence function of the laser diode as mentioned above.

IV. Conclusion

We have proposed and demonstrated a novel linearzing method of optical frequency-sweep of a laser diode for FMCW reflectometry. In order to linearly sweep the optical frequency, the beat signal of a simple reference interferometer made of a piece of single-mode optical fiber is phase-compared with an external reference signal by a lock-in amplifier, and the resultant error signal is fed back to the injection current of the laser diode and correct the original modulating injection current of the laser diode. The linearity of the proposed method has been experimentally confirmed by applying this frequency-swept laser diode to the FMCW reflectometry. Resultingly, the improvement of the linearity has been estimated to be about 10 dB. The backscattered light in optical waveguide devices is measured by the FMCW reflectometry using the proposed frequency-swept laser diode, and the propagation loss of a potassium-ion-exchanged single-mode glass waveguide is successfully evaluated to be about 1.0 dB/cm. The proposed linearly frequency-swept laser diode is applicable as a light source not only for the FMCW reflectometry but also for the frequency-division multiplexed sensor system.

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