High-resolution FMCW reflectometry using a single-mode vertical-cavity surface-emitting laser

High-Resolution FMCW Reflectometry Using a Single-Mode Vertical-Cavity Surface-Emitting Laser

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***Abstract*—High-resolution frequency-modulated continuous-wave (FMCW) reflectometry is realized by using a single-mode vertical-cavity surface-emitting laser (VCSEL) as a frequency-swept light source for the first time. The optical frequency of the VCSEL is swept by the injection current modulation. The experimental spatial resolution of 250 μm was achieved, which is the best value when an injection current tuned laser diode is used as a frequency-swept light source.**

***Index Terms*—Frequency-modulated continuous-wave (FMCW) reflectometry, optical frequency domain reflectometry (OFDR), reflectometry, vertical-cavity surface-emitting laser (VCSEL).**

I. Introduction

FREQUENCY-MODULATED continuous-wave (FMCW) reflectometry, which is also called as optical frequency domain reflectometry (OFDR), has been developed for absolute optical ranging and for measuring reflections of fiber connectors, packaged optical devices and optical integrated devices [1]–[9]. Fig. 1 shows the configuration of the FMCW reflectometry and the instantaneous optical frequency change of the reflected and the reference lights. The FMCW reflectometry is composed of a frequency-swept laser source and a two-beam interferometer, and a device under test is located in an arm of the interferometer. The reflected light from the device under test interferes with the reference light from the another arm of the interferometer on a photodetector. When the optical frequency of the laser source is swept in triangular waveform as is shown in Fig. 1(b), the beat frequency f_b is given as;

$$f_b = 2 f_m \Delta F \times \tau \tag{1}$$

where f_m and ΔF are the repetition frequency and the tuning range of the optical frequency sweep, respectively, and τ is the differential time delay between the two lights. The interference signal has a beat frequency corresponding to the optical path difference (OPD), and then the device under test is characterized by the Fourier analysis of the interference signal. The spatial resolution δz is given as [3], [4];

$$\delta z = \frac{c}{2n\Delta F}. \tag{2}$$

Manuscript received August 27, 2010; revised February 07, 2011; accepted March 14, 2011. Date of publication March 22, 2011; date of current version May 11, 2011.

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Digital Object Identifier 10.1109/LPT.2011.2131124

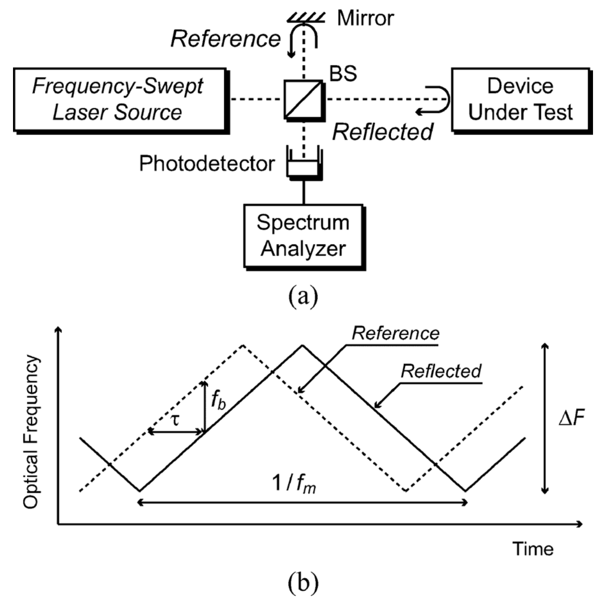
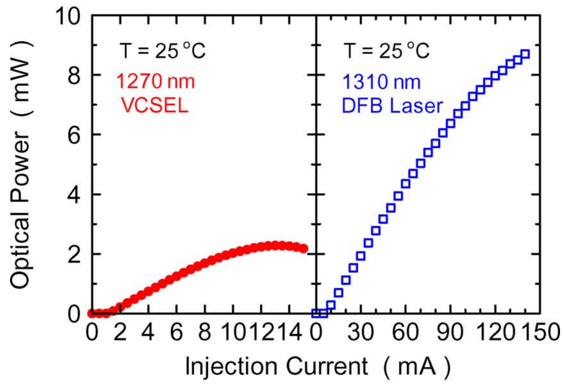


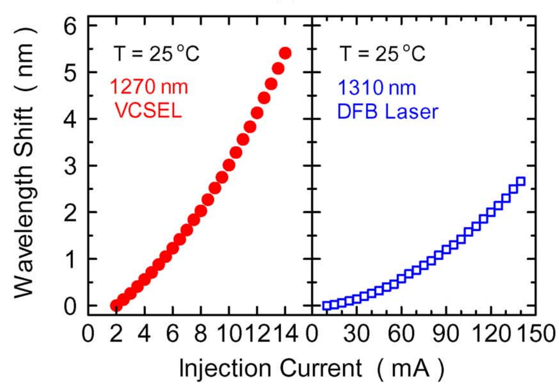
Fig. 1. Configuration of FMCW reflectometry and the waveform of the optical frequency change of the two beams in the FMCW reflectometry. (a) Configuration (BS: beam splitter). (b) Waveform of optical frequency change.

where c is the light speed in vacuum, and n is the refractive index of the device under test.

A Fabry–Pérot laser or a distributed feedback (DFB) laser is often used as the frequency-swept light source because the optical frequency can be easily changed by the injection current modulation or by the temperature tuning. In [1], the optical frequency of a Fabry–Pérot laser was swept by the injection current modulation and the propagation loss of a glass optical waveguide was estimated with the spatial resolution of 1 mm at 80 cm (which corresponds to 1.5 mm in air). In [2], the optical frequency of a DFB laser was tuned by the temperature tuning to achieve large optical frequency change, and the spatial resolution of 50 μm in a few centimeter-long InP optical waveguide (which corresponds to about 150 μm in air) was achieved. However the tuning speed was 20 s and then real-time measurements are impossible. In [3], the optical frequency of a DFB laser was swept by the injection current modulation, and the spatial resolution of 400 μm for a 6 cm-long optical fiber (which corresponds to 600 μm in air) was achieved. In [4], a continuously tunable external cavity laser was used a frequency-swept laser source, and the spatial resolution of 22 μm in a fiber (which corresponds to about 33 μm in air) was achieved over 35 m of the measurement range. Although an external cavity laser is useful as the frequency-swept laser source in the FMCW reflectometry, the laser cavity should be carefully configured to avoid



(a)



(b)

Fig. 2. Optical power change and wavelength shift of a VCSEL and a DFB laser against the injection current. Slope efficiencies are 0.25 and 0.081 mW/mA for a VCSEL and a DFB laser, respectively. The wavelength tuning rates are $0.2 \sim 0.7$ nm/mA and $0.01 \sim 0.04$ nm/mA for a VCSEL and a DFB laser, respectively. (a) Optical power change. (b) Wavelength shift.

mode hopping during the frequency sweep because the interference signal may be discontinuous due to the mode hopping and then the spatial resolution may be degraded. The measurement range is restricted by the coherence length of the light source because the FMCW reflectometry utilizes interference of lights. If we need long-range measurement, then a narrow linewidth laser source is necessary.

Fig. 2 shows the measured optical power change and the wavelength shift of a vertical cavity surface emitting laser (VCSEL) operating at 1270 nm and a DFB laser operating at 1310 nm against the injection current at 25°C. Although the optical power of the VCSEL is smaller than the DFB laser, the wavelength tuning rate of the VCSEL ($0.2 \sim 0.7$ nm/mA) is one order of magnitude larger than that of the DFB laser ($0.01 \sim 0.04$ nm/mA). Such a large wavelength tuning rate is caused by large temperature change in the VCSEL cavity due to the high carrier density attributed to the small laser cavity volume. As a result, the spatial resolution of FMCW reflectometry can be enhanced by using the VCSEL as a frequency-swept light source.

In this Letter, we demonstrate the FMCW reflectometry using a single-mode VCSEL for the first time. The optical frequency of the VCSEL is swept by changing the injection current, and the spatial resolution of 250 μm in air is achieved, which is, to our knowledge, the best spatial resolution when an injection current tuned laser diode is used as the frequency-swept light source.

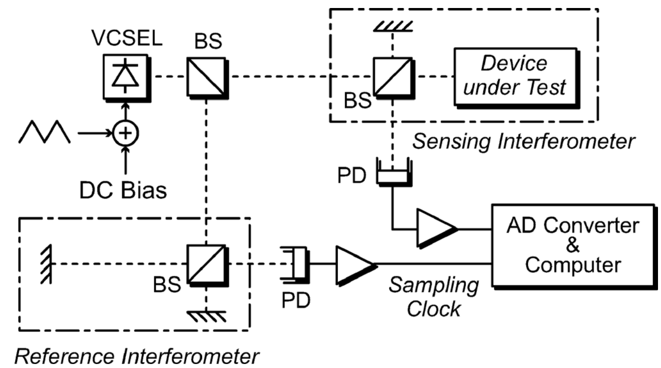


Fig. 3. Experimental setup of the FMCW reflectometry using a VCSEL (BS: beam splitter; PD: photodiode).

II. Experiments

Fig. 3 shows the experimental setup of the FMCW reflectometry. A single-mode VCSEL operating at 1270 nm is used as a light source and the optical frequency is swept by modulating the injection current with a triangular signal. The emitted light from the VCSEL is divided into two beams; one beam is launched into the sensing interferometer, and the interference signal is sampled by a 12-bits analog-to-digital converter (AD converter) and then is stored in the computer for the Fourier analysis. The other beam is launched into the reference interferometer and the interference signal is used to generate the sampling clock signal of the AD converter [2]–[4], [9]. Such a sampling scheme is very useful to enhance the spatial resolution because the optical frequency cannot be linearly swept by linearly sweeping the injection current [5], [6], [10]. In this sampling scheme, the OPD of the reference interferometer L_R should be more than double of the OPD of the sensing interferometer L_S to satisfy the sampling theorem between the sampling clock signal and the sensing signal. In our experiments, $L_R = 21$ cm, and then $L_S < 10.5$ cm, which gives the one-way optical path difference is less than 5.25 cm. The reflecting location z is calculated as;

$$z = \frac{1}{2}\frac{L_R}{2}\frac{D}{\frac{N}{2}} \tag{3}$$

where N is the total number of the sampled data, D is the data number after the FFT, $L_R/2$ is the one-way optical path difference in the reference interferometer, and the coefficient 1/2 means the limitation to satisfy the sampling theorem between the sampling clock signal and the sensing signal.

The spectral linewidth of the VCSEL was measured by the delayed self-heterodyne method to be about 80 MHz, which is about ten times wider than that of DFB lasers. The relative intensity noise (RIN) of the VCSEL is -130 dB/Hz at 1 MHz and -152 dB/Hz above 5 MHz, which is almost the same with DFB lasers.

In the experiments, the repetition frequency of the modulation signal is $f_m = 100$ Hz, the DC current is 8 mA, and the modulation current change $\Delta I = 10$ mA. From Fig. 2, the wavelength change of the VCSEL is about 4.5 nm at the above condition, and the resultant optical frequency change is about 830 GHz. The theoretical spatial resolution is then expected to be about 180 μm for $n = 1.0$ from (2). The total number of the sampled data is $N = 2048$. The Blackman window function was used for

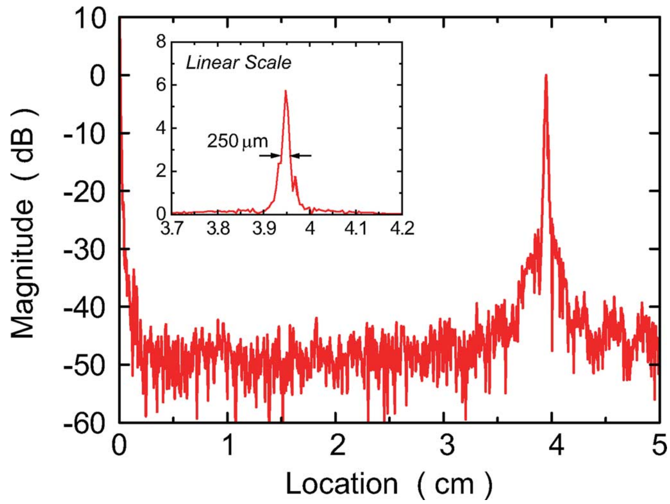


Fig. 4. Measured reflection profile for a mirror located at 4 cm.

the Fourier analysis. The amplitude of the interference signal is also triangularly changed due to the injection current change. In the experiments, the amplitude change in the interference signal was compensated by dividing the interference signal with the optical power change measured by an additional photodetector (not shown in Fig. 3).

Fig. 4 shows the measured reflection profile when a mirror is used as the device under test. The one-way optical path difference is about 4 cm. A fine reflection profile is observed around 4 cm and the signal-to-noise ratio (SNR) is about 45 dB, which is smaller than the dynamic range of the AD converter (72 dB). The SNR is mainly governed by the phase noise of the VCSEL because of the wide spectral linewidth of the VCSEL [11]. A narrow linewidth VCSEL should be used to detect the Rayleigh backscattering in optical fibers and optical waveguides. The inset shows the reflection profile around 4 cm in a linear scale. The spatial resolution defined as the full-width at half maximum (FWHM) is 250 μm, which is, to our knowledge, the best spatial resolution when the injection current tuned laser diode is used as a frequency-swept light source. The experimental spatial resolution is degraded as compared to the expected theoretical spatial resolution (180 μm) due to the Blackman window for the FFT analysis.

Fig. 5 is the measured reflection profile when an 1 mm-thick slide glass is located at 4 cm and is used as the device under test. Three fine reflection profiles are clearly observed. The two reflection profiles around 4 cm are caused by the Fresnel reflection at the input and the output surfaces of the slide glass, and the reflection profile around 0.15 cm is caused by the interference between the input and the output surfaces of the slide glass. The spatial resolution (FWHM) is about 200 $\sim$ 250 μm for the three reflections.

III. Conclusion

We have developed the FMCW reflectometry using a single-mode VCSEL as a frequency-swept light source. The optical wavelength change of the VCSEL is larger than the DFB laser, and then the spatial resolution is enhanced to submillimeter range. The spatial resolution of 250 μm was experimentally achieved, which is, to our knowledge, the best spatial resolution when the injection current tuned laser diode is used as a frequency-swept light source. The spectral linewidth of the VCSEL we used is about 80 MHz and then the measurement range is limited to less than 1 m. However a VCSEL has wide wavelength tuning range with a smaller injection current change, and then the FMCW reflectometry using a VCSEL can be used in moderate spatial resolution (0.1 $\sim$ 1 mm), low-power operation, short range and low-cost applications, for examples, 2-dimensional object profiling and distance measurement for machine control.

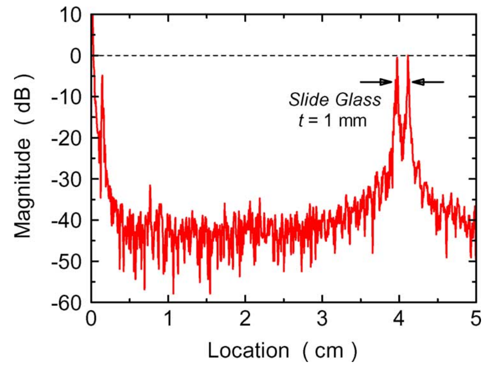


Fig. 5. Measured reflection profile for an 1-mm-thick slide glass located at 4 cm.

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