140-nm Quasi-Continuous Fast Sweep Using SSG-DBR Lasers

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***Abstract*—We demonstrate a single-mode and fast wavelength swept light source by employing superstructure-grating distributed Bragg reflector (SSG-DBR) lasers for use in optical frequency-domain reflectometry optical coherence tomography. A noteworthy feature is that our laser employs a thermal drift compensator (TDC). By utilizing the TDC, we achieved a fast wavelength sweep without any unexpected mode hopping. We newly designed and fabricated SSG-DBR lasers covering the following four wavelength bands: 1496–1529, 1529–1564, 1564–1601, and 1601–1639 nm. We achieved a stable operation for the whole wavelength range. A wide wavelength tuning of 143 nm was achieved within 1.4 ms. A single-mode, wide, and fast wavelength sweep was demonstrated.**

***Index Terms*—Optical coherence tomography (OCT), superstructure-grating distributed Bragg reflector (SSG-DBR) laser, thermal drift compensation, thermal management.**

I. Introduction

WAVELENGTH tunable lasers are attractive for various applications in, for example, photonic network systems and medical sensing systems that employ optical coherence tomography (OCT). The mechanism and experimental setups have already been reported [1]–[4]. For use as light sources in OCT systems, tunable lasers require a wide wavelength tuning range and a fast wavelength sweep. A wide wavelength tuning range enhances the spatial resolution, and a fast tuning speed improves the clarity of the OCT image, which is blurred because of movement by the human subject. There are two main types of fast wavelength swept lasers: the external cavity laser [1]–[4] and the monolithically integrated semiconductor laser. External cavity lasers offer a very fast wavelength sweep, and so a very clear OCT image is obtained. The lasers operate in the multimode optical spectrum and it is difficult to keep their output powers constant. In contrast, monolithic semiconductor lasers provide single-mode and constant power operation, which offers the possibility of improving the OCT image. We have developed a monolithically integrated semiconductor laser called a superstructure-grating distributed Bragg reflector (SSG-DBR) laser [5].

The other advantage of the SSG-DBR laser is that the lasing wavelength can be set at any value in the whole wavelength tuning range. This flexibility enables us to achieve step tuning with a constant frequency spacing (K-space linear tuning). When the sampling is performed with an even frequency step, we can apply a fast Fourier transform (FFT) to the data. An FFT greatly reduces the processing time and enhances the dynamic range of the OCT image. Recently, this laser has attracted attention as a medical sensing light source, and is a candidate for use in optical frequency-domain reflectometry OCT [6].

The wavelength tuning response time of the SSG-DBR laser is estimated to be several nanoseconds, and the time is electrically determined by the injected carrier lifetime. However, there is an unintentional wavelength drift caused by the thermal drift that results from tuning current injection. This drift requires a much longer time to stabilize (from several milliseconds to several seconds) than the carrier lifetime. We have reported a thermal compensation structure [7], which is monolithically integrated parallel to the mesa stripe of a C-band SSG-DBR laser [8]. This laser can shorten the wavelength transient time when the tuning current is switched. We have achieved an accurate frequency sweep, which enables us to apply an FFT directly to the sampled data.

In the present work, we demonstrate a wide and fast wavelength sweep with single-mode operation using thermal compensation in SSG-DBR lasers. We newly designed and fabricated SSG-DBR lasers operating in the S-, L^{-}-, and L^{+}-bands, and greatly expanded the total tuning range to more than 140 nm. The SSG-DBR lasers cover wavelength ranges of 1496–1532 nm (S-band laser), 1530–1567 nm (C-band laser), 1561–1601 nm (L^{-}-band laser), and 1601–1639 nm (L^{+}-band laser). By expanding the tuning range from 35 to 140 nm, we can greatly improve the spatial resolution of the OCT image from 20 to 5 μm. This enables us to discover smaller pathogens (e.g., cancers). We demonstrate a rapid wavelength sweep with a wavelength range of more than 140 nm by serially driving the four SSG-DBR lasers.

II. Laser Structure

Fig. 1 shows a photograph (top view) of our SSG-DBR laser. The laser consists of a semiconductor optical amplifier (SOA) region, a front SSG-DBR region, an active region, a phase control region, and a rear SSG-DBR region, and their respective lengths are 400, 310, 350, 80, and 610 μm. The length of the active region of the S-band laser was designed to be 50 μm shorter, which offers a flat gain spectrum, and that of the L^{+}-band laser was designed to be 50 μm longer to achieve a large output

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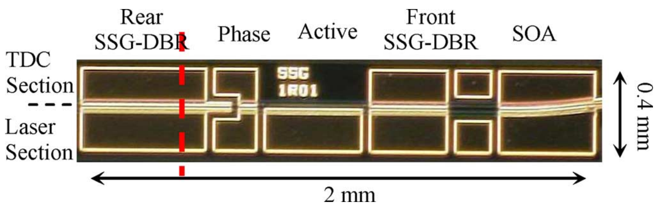

Fig. 1. Photograph of SSG-DBR laser with TDC mesa.

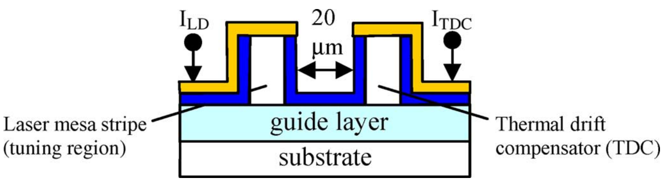

Fig. 2. Cross-sectional view of a laser with a temperature compensating mesa stripe.

power than those of the C- and L^{-}-band lasers. The active multiquantum-well layer and the passive bulk layer were butt-jointed together. The respective bandgap wavelengths of the active layers of the S-, C-, L^{-}-, and L^{+}-band SSG-DBR lasers were 1515, 1550, 1585, and 1620 nm, and those of the passive layers were 1360, 1400, 1400, and 1470 nm. The detuning of the passive layer was optimized to achieve stable operation in the S- and L^{+}-band lasers.

A noteworthy feature is that our new laser has a thermal drift compensator (TDC) mesa stripe parallel to the laser mesa stripe with a 20-μm spacing as shown in Fig. 2. Here, I is the current injected into the mesa stripe, and the subscripts indicate laser or TDC sections. When we inject TDC current $I_{\rm TDC}$, the TDC mesa stripe acts as an electrical heater. The basic idea behind our study was to maintain the optical waveguide temperature. This means that we have to keep the total power injected into the two stripes constant. We will describe wavelength tuning with the TDC in detail later.

III. Thermal Drift Compensation Method

First, we describe a case using no TDC current, which corresponds to the thermal drift mechanism in a conventional DBR laser with no TDC mesa stripe. In our laser module, the laser chip is mounted on heatsink with a thermistor, and the heatsink unit is mounted on a thermoelectric cooler (TEC). When the wavelength tuning current of the laser is increased, the amount of generated heat also increases. This heat is then transmitted to the thermistor through the heatsink, and the TEC current is controlled to keep the thermistor resistance constant. The final value of the TEC current and the temperature of the laser mesa stripe depend on the amount of heat that is generated, because heat resistance also influences the temperature. It should be noted that the waveguide temperature deviates when the amount of generated heat changes. During the lasing wavelength adjustment process, the wavelength is accurately measured once the temperature has been completely stabilized. Generally several seconds are required for the temperature to stabilize around the laser mesa stripe. As mentioned above, the waveguide temperature is different for each wavelength grid point. Here we describe a case where the lasing wavelength is swept. During a rapid wavelength sweep with an SSG-DBR laser, the temperature of the laser mesa stripe is averaged to a certain value, which reflects the temperatures of all the wavelength channels. Hence, the lasing wavelength during a rapid wavelength sweep deviates from the frequency established under static conditions. This thermal drift is dominant in DBR lasers, and unfortunately the response time is very slow. The temperature deviation causes a large frequency deviation and a lot of unexpected mode hopping [8], which is not permissible in OCT. The frequency deviation was 20 GHz without the TDC [8], and this is influenced by the thermal resistance (e.g., the thickness of the substrate, and the contact of the die bonding).

Next, we describe a case with TDC current. For practical operation, if we increase the power to the laser stripe for tuning, we must then provide compensation by reducing the power to the TDC stripe, and vice versa. When the total power is kept at a constant value, the amount of generated heat is also constant, and there is no thermal drift. The thermal features, including the time constants of the laser mesa and TDC mesa, are almost the same, because we used a common structure for the laser mesa and the TDC mesa. This TDC method [8] is applied to the SOA, the front SSG, the phase, and the rear SSG region. The individual powers and the TDC current are easily determined from the current versus power curves, which have been measured previously [8].

We used this method both to adjust the frequency grid during static operation and to sweep the frequency during dynamic operation. Thus, the wavelength drift can be suppressed, and the laser realizes a fast wavelength sweep. The thermal wavelength drift can be sufficiently suppressed without dynamically regulated current control, which takes a transient thermal response into account. The temperature and the wavelength during dynamic operation were almost the same as those during static operation [8]. Hence, the accuracy is constant for various sweep speeds.

IV. Experiments and Results

A. Characteristics in Static Operation

When operating the SSG-DBR lasers, we drove all the regions of the laser and TDC sections. The total electrical input powers for the SOA, front SSG-DBR, rear SSG-DBR, and phase control region were kept at 250, 70, 90, and 30 mW, respectively. Fig. 3 shows the superimposed spectra of the S-, C-, L^{-}-, and L^{+}-band SSG-DBR lasers, which were measured during static operation. We set the frequency grid of each laser at 43 or 44 channels with a frequency spacing of 100 GHz. Each module output power of 10 dBm, and stable operation with a submode suppression ratio (SMSR) of more than 40 dB were achieved for the whole tuning range. The currents injected into the laser and TDC sections for the front and rear SSG-DBRs are plotted in Fig. 4. It should be noted that the curves of the TDC currents are the reverse of that of the tuning current. The TDC currents were accurately set to maintain the total power.

In this experiment, the TDC current values were much larger than those of the tuning currents in Fig. 4. We set the total powers to be sufficiently large to maintain large available ranges of the tuning currents, because we were not able to estimate the maximum values of the tuning currents. Next, we can reduce

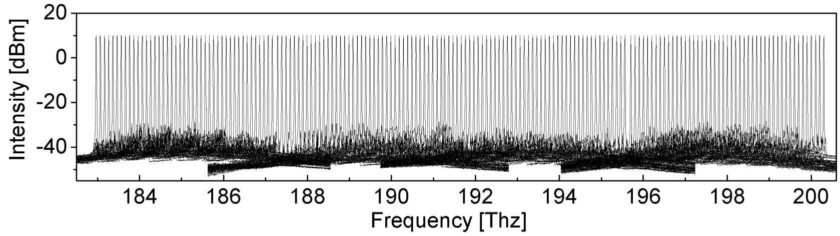

Fig. 3. Superimposed spectra measured during static operation. The SMSR is more than 40 dB for the whole tuning range.

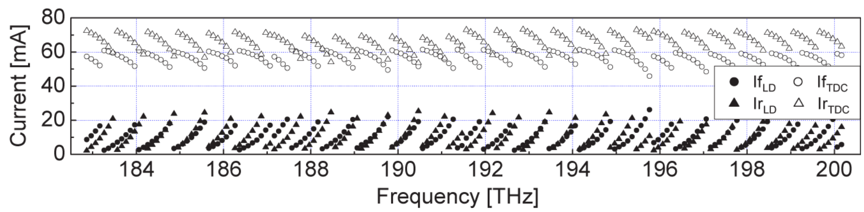

Fig. 4. Tuning current and TDC current injected into front and rear SSG-DBR.

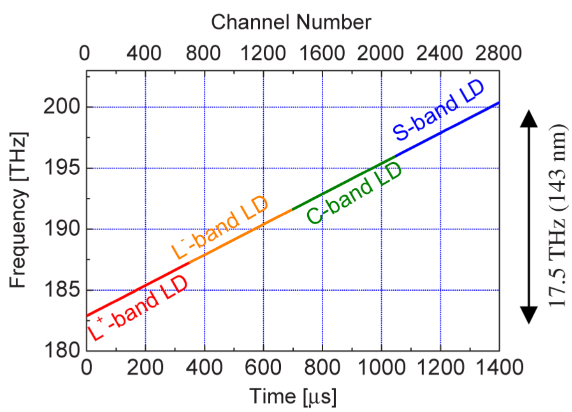

Fig. 5. Time-resolved spectra. Four SSG-DBR lasers were serially and synchronously swept.

the TDC current to a level which is comparable with that of the tuning current.

B. Characteristics in Fast Wavelength Sweep

We demonstrate a fast wavelength sweep using the S-, C-, L^--, and L^+-band SSG-DBR laser modules. To achieve this we set the frequency grid number of each laser at 700 channels with a frequency interval of 6.25 GHz. The total number of frequency grids was 2800 channels (700 channels $\times$ 4 lasers), and the total tuning range was greatly expanded to 143 nm (17.5 THz). The time interval for the wavelength sweep was set at 500 ns/channel. We swept the wavelengths of the four lasers serially and synchronously. The total time needed to scan all 2800 channels was 1.4 ms. The dynamic change in the frequency was measured with the time-resolved spectrum method. The sampling time of the digitizing oscilloscope was set at 100 ns. There were five sampling points for each frequency channel, and we plotted the fourth sampling point on a graph. Fig. 5 shows the time-resolved spectra. Frequency data for 2800 points are plotted in Fig. 5. We achieved a rapid frequency sweep with a range of more than 140 nm (17.5 THz) without any unexpected mode hopping.

V. Conclusion

We demonstrated a fast wavelength sweep with a time interval of 500 ns/channel by serially and synchronously operating S-, C-, L^--, and L^+-band SSG-DBR lasers equipped with TDCs. A total tuning range of more than 140 nm was achieved by sweeping 2800 frequency channels, and this provided a spatial resolution of 5 μm. A fast and accurate wavelength sweep was realized by suppressing thermal drift. SSG-DBR lasers with TDCs are suitable for use as fast swept light sources. We achieved a wide quasi-continuous wavelength sweep with a range of more than 140 nm within 1.4 ms by using plasma effect wavelength tunable lasers.

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