High-power and Wide-band 1.3-µm Super Luminescent Diode for Optical Coherence Tomography

Mitsuru Sugo† *and Yasuo Shibata*

Abstract

In this paper, we describe high-power (>50 mW), wideband (>50 nm) 1.3-µm super luminescent diodes (SLDs). The SLDs have a tilted stripe and both facets have a window structure and antireflection coating. This design reduces the spectrum ripple (<0.4 dB). An SLD module exhibited a high coupling efficiency of over 70% and a high power of more than 30 mW in a single-mode fiber. These SLDs are suitable for use in optical biological imaging.

1. Introduction

Super luminescent diodes (SLDs), which emit low-coherent light, are used in optical measurement systems, such as fiber gyroscopes [1] and optical time domain reflectometers (OTDRs) [2]. Recently, they have become crucial elements for biophotonic imaging techniques such as optical coherence tomography (OCT)* [3]-[5]. OCT is already being put to practical use in retinal examination equipment, which uses a 0.83-µm SLD as a light source [3]. However, there are still demands to extend the capabilities of OCT. For instance, integrating OCT with endoscopes would make it possible not only to observe the outer layers of internal organs but also to obtain information about their inner structures [5], which would be helpful in the early detection and treatment of cancer. These applications require SLDs that emit light with a wavelength of 1.3 µm [5]. In this region, water and hemoglobin (the constituents of living tissue that absorb the most light) both exhibit little light absorption and the light is less susceptible to scattering, so living tissue exhibits the greatest transparency at this wavelength. Consequently, the light can penetrate deep into the body from the surface of the skin, allowing deep tomographic imaging.

These applications also require an SLD with higher power and larger bandwidth than conventional ones [6]. For *in-vivo* OCT imaging, the information-bearing signals tend to be weak and obscured by noise. Accordingly, there has been a growing need for a high-output light source that can be used to obtain highly precise data signals from living subjects. The bandwidth of light emitted from the light source has a large effect on the resolution of OCT images. A broader bandwidth increases the resolution, resulting in images with greater detail and allowing finer tissue structures to be observed.

In this paper, we present 1.3-µm SLDs with a chip output power above 50 mW and a large bandwidth of more than 50 nm. A novel structure reduced spectrum ripple to less than 0.4 dB even above 50 mW. An SLD module exhibited a high coupling efficiency of more than 70% and a high power of more than 30 mW in a single-mode fiber. The cavity length dependence of the power and bandwidth are also discussed.

2. SLD structure

An InGaAsP multiple quantum well (MQW) active layer with separate confinement heterostructure layers and a pn-buried heterostructure were grown by metalorganic vapor phase epitaxy. To suppress spectrum ripple due to lasing in the Fabry-Perot mode during high-power operation, we used a tilted stripe

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* OCT uses low-coherence interferometry to produce a two-dimensional image of optical scattering from internal tissue microstructures. Only the coherence length of the light sources limits the depth resolution of OCT.

(around 1 µm wide), gave both facets a window structure, and applied an antireflection coating to both facets. These techniques reduced the reflectivity of the facets. The structure of our SLD is schematically illustrated in **Fig. 1**.

The correlation between the root-mean-square (rms) maximum spectrum ripple and chip output power for the novel SLDs is shown in **Fig. 2**, with data for the old type of SLDs also shown for comparison. The old-type SLDs have a straight stripe, an antireflection coating on only the front facet, and a window structure on only the rear facet. Spectrum ripples for the old-type SLDs increase sharply with increasing output power and result in lasing above about 10 mW, which is undesirable. In our new SLDs, on the other hand, spectrum ripple was suppressed to below 0.4 dB even at high output power above 50 mW.

3. SLD output power

The suppression of spectrum ripple enabled us to obtain higher power using a longer cavity length. **Figure 3** shows the correlation between the measured output power and cavity length for our SLDs (closed circles). For comparison, data for a Fabry-Perot laser diode (FP-LD) are also shown (open circles). The measurement condition was a constant current per unit length of 100 mA/mm. For an SLD, a simplified model can express output power (P) as a function of cavity length (L) as [7]

$$P \propto \exp\,[(\Gamma g_m - \alpha_i)L] - 1, \qquad (1)$$

where Γ is the confinement factor, g_m is the material gain, and α_i is the internal loss. The solid red line in Fig. 3 is the fitting curve obtained from eq. (1). Equation (1) can explain the correlation between the output power and cavity length.

Next, let us see how this compares with an FP-LD with both facets cleaved. The equation for the power of an LD as a function of cavity length is

$$P \propto J_{op} / [\alpha_i / \ln(1/R) + 1/L], \qquad (2)$$

where J_{op} is the current per unit length and R is the facet reflectivity. It is well known that an LD outputs more power than an SLD. However, as the cavity becomes longer, the rate of the increase in the power gradually drops (dotted blue line), while that for the SLD (solid red line) rises. Eventually, the powers become comparable. This dispels our preconception that an SLD cannot emit high-power light like an LD.

4. Bandwidth and module performance of SLD

The correlation between the 3-dB bandwidth (full width at half maximum) of the spectrum and cavity length is shown in **Fig. 4**. The open circles are measured values and the line is a guide for the eye. Current density was again constant at 100 mA/mm. The bandwidth decreased gradually with increasing cavity length. The 3-dB bandwidth value of 120 nm obtained by extrapolating the cavity length to zero

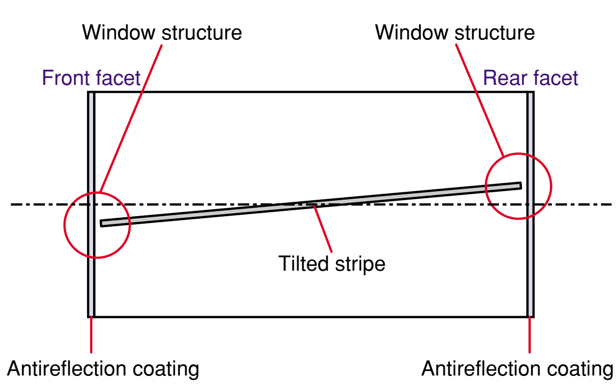

Fig. 1. Schematic structure of our SLD.

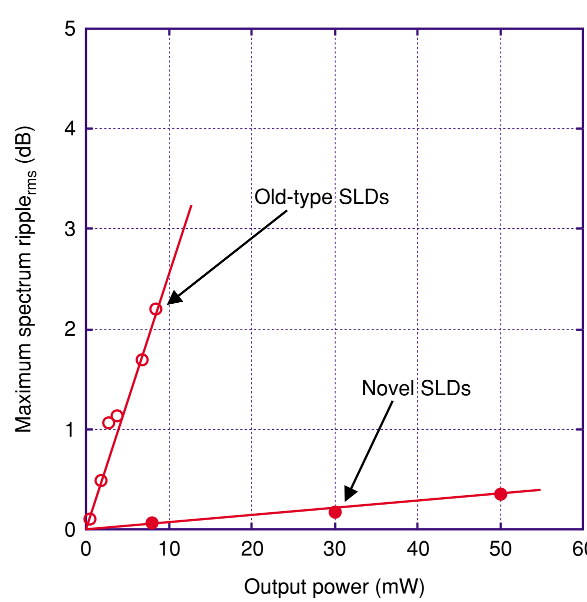

Fig. 2. Correlation between maximum spectrum ripple and chip output power.

corresponds to the bandwidth of spontaneous emission from the MQW active layer. The bandwidth was also a function of the injection current density. **Figure 5** shows (a) typical light-current characteristics obtained in the current range up to 600 mA and (b) the spectrum at a current per unit length of 233 mA/mm (P_o = 50 mW). In this case, the cavity length was 1.5 mm. Normally, there is a trade-off between bandwidth and optical output and this has prevented the development of SLD light sources that combine a high optical output with a large bandwidth. However, our SLD achieved both high output power of over 50 mW and large bandwidth of more than 50 nm simultaneously.

We have also developed an SLD module using a hermetically sealed 14-pin butterfly package shown

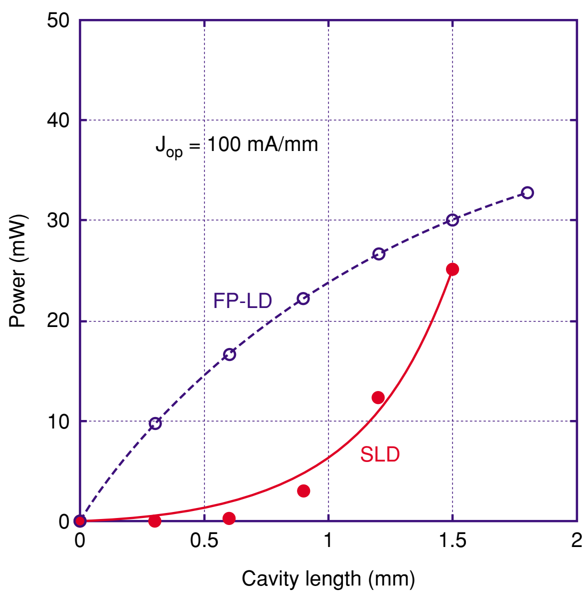

Fig. 3. Correlation between output power and cavity length.

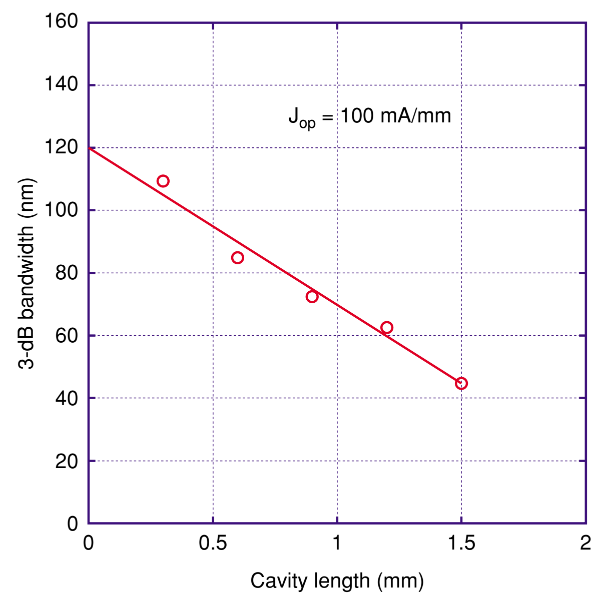

Fig. 4. Correlation between 3-dB bandwidth and cavity length.

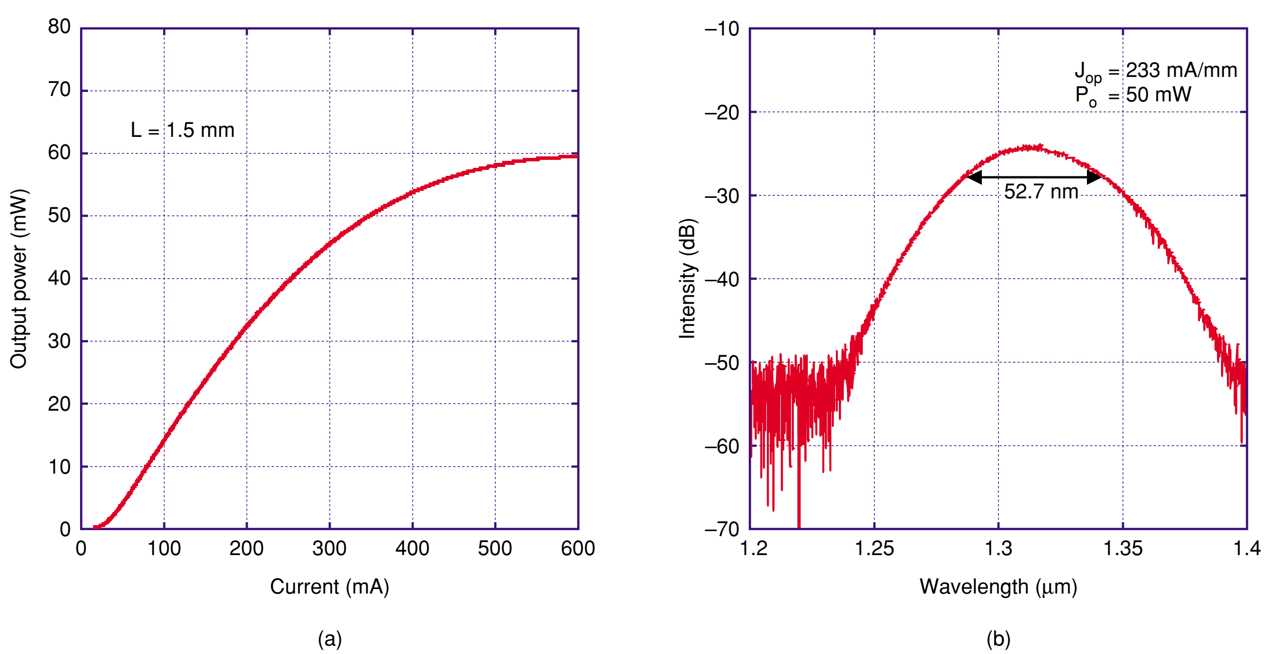

Fig. 5. (a) Typical light-current characteristics and (b) spectrum.

in **Fig. 6**. **Figure 7** shows typical measured characteristics of light output from a single-mode fiber attached to the module versus current supplied to the module and the measured voltage-current characteristics of the module. The coupling efficiency exceeded 70% and the output power was more than 30 mW. This high coupling efficiency helped to reduce the module's power consumption. At 30 mW, the operating current was as low as 300 mA and the operating voltage was as low as 1.7 V.

5. Conclusions

In summary, we demonstrated 1.3-µm SLDs with high chip output power (>50 mW) and large bandwidth (>50 nm). The novel structure ensured low spectrum ripple (<0.4 dB) even above 50 mW. An SLD module exhibited a high coupling efficiency of over 70% and a high power of more than 30 mW in a single-mode fiber. These SLDs are suitable for use in optical biological imaging systems.

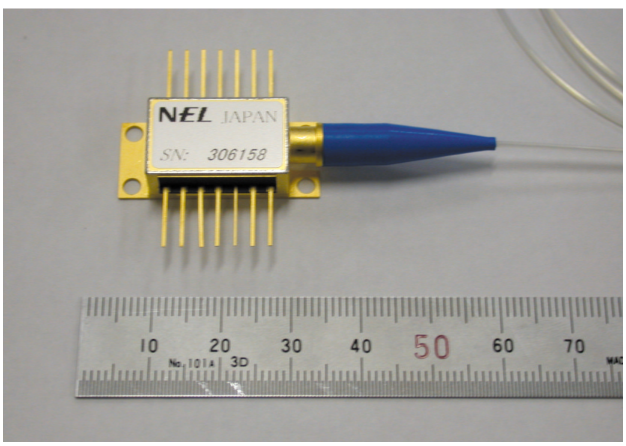

Fig. 6. SLD module using a hermetically sealed 14-pin butterfly package.

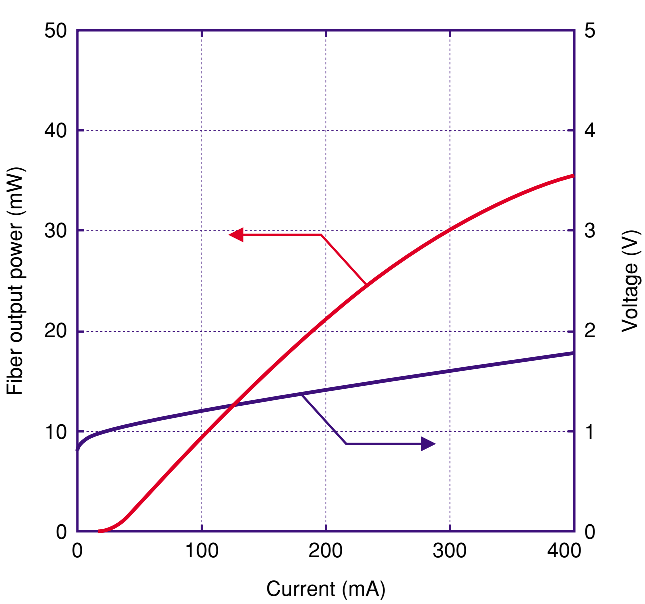

Fig. 7. Typical light-output power and voltage/current characteristics of SLD module.

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