1.7-μm Broadband Light Source and Applications

Jun Ono, Hiroshi Mori, Yoshiharu Shimose, Tetsuya Suzuki, Atsushi Yamada, Kazuaki Mise,
Yasuaki Nagashima

[Summary] The 1.7-μm band suffers little absorption loss from water molecules and can be used to evaluate the presence of organic solvents in aqueous solution from optical absorption peaks caused C-H bonds.[1), 2)] We have worked in cooperation with Osaka Prefectural University to develop a 1.7-μm band ASE[3)] light source composed of a Thulium (Tm^{3+}) doped fiber amplifier (TDFA) pumped by an Anritsu 1.2-μm LD module. This article explains the developed 1.7-μm band ASE light source with optical output improved by combination with a 1.65-μm band SLD module and describes the application of this light source in a system for evaluating the alcohol concentration of Japanese sake rice wine using a near infrared optical spectroscope system.

1 Introduction

The Anritsu Optical Devices Development Group has been focusing efforts on commercial development of a high-power 1.48-μm semiconductor laser diode (LD) for pumping an Erbium-Doped Fiber Amplifier (EDFA) with the requirement of expanding customers' applications in the high-speed optical transmission market. Additionally, the following describes our active R&D into light-emitting elements for the near-infrared spectrum with expected wide future applications in optical sensing.

- Development of Distributed FeedBack Laser Diodes (DFB-LD) in the near-infrared wavelength region and examination of application fields
- Development of long-wavelength Super Luminescent Diodes (SLD) with excellent optical coupling to single mode fiber

Near-infrared spectroscopic analysis using LDs is well known[4)] and Anritsu has successfully developed a methane gas detector using a 1.65-μm band DFB-LD[5), 6)]. The wavelength range from 1.7 to 1.8 μm has low optical absorption due to water molecules in the measurement environment and is generally known as an 'optical window.' In addition to gas measurements, it can also be used to measure the presence of organic materials dissolved in water in a clear glass container.

We have successfully used a 1.2-μm Fiber Bragg Grating (FBG) LD module to pump a Thulium (Tm^{3+}) Doped Fiber Amplifier) (TDFA) and generate Amplified Spontaneous Emission (ASE) to measure the concentration of organic solvents such as isopropyl alcohol and dimethyl sulfoxide in solution as well as cholesterol solvents to validate the usefulness of long-wavelength, broadband light sources[7) to 13)].

However, increasing the measurement accuracy requires solving problems about increasing the output power. We have examined how to increase the optical power by combining the broad optical waveform and optical output of a 1.65-μm band SLD module with the above described broadband light source.

This article introduces the structure and characteristics of a 1.7-μm broadband light source and also explains tests to evaluate the concentration of alcohol in Japanese *sake* rice wine by connecting the developed light source to a spectroscopic evaluation system.

2 1.7-μm Broadband Light Source

2.1 Structure

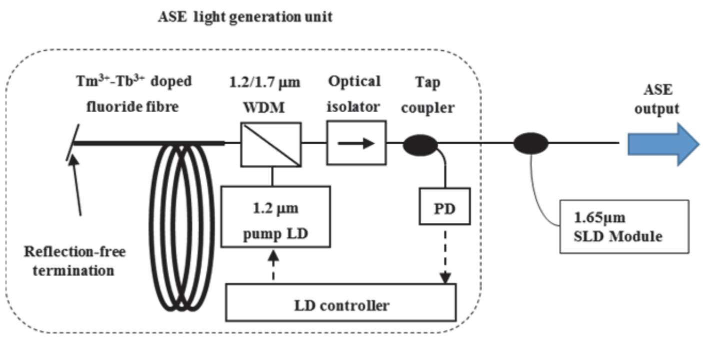

Figure 1 1.7-μm Broadband Light Source

Figure 1 shows the structure of the 1.7-μm broadband light source. It is composed of an ASE light source using a TDFA and the 1.65-μm SLD module. The TDFA is composed of a Thulium (Tm^{3+}) doped fiber pumped by a 1.2-μm band LD module, a 1.2-μm/1.7-μm band WDM coupler, and an optical isolator. The thallium-doped fiber relative refractive index difference, cutoff frequency, Tm^{3+} doping concentration, and fiber length are 1.6%, 1 μm, 6000 ppm, and 1 m, respectively.

2.2 1.2-μm Pump LD Module

Like the 1.65-μm SLD module described later, the 1.2-μm band pump LD module uses a 14-pin butterfly package. The details of the structure are described in the next section. The Far-Field pattern (FFP) LD element is oriented at 20° to the horizontal and vertical axes; the beam form is nearly circular. In addition, an aspherical lens is used to achieve and an optical fiber coupling efficiency of 80%. The LD element is held at a constant 25°C reference operating temperature using a thermistor and Thermo Electric Cooler (TEC). In addition, a photodiode for monitoring the LD output is positioned at the rear of the LD.

A FBG matching the lasing wavelength is used to connect the single-mode fiber (optical fiber hereafter) to this module. An anti-reflection (AR) coating on the output facet suppresses reflections to form an external laser oscillating resonator between the FBG and LD. The oscillation wavelength is fixed to 1.24 μm in the operating range and the optical output can be varied at this wavelength. The maximum fiber output power of 120 mW was obtained.

2.3 1.65-μm SLD Module

Figure 2 shows the external appearance of the 1.65-μm SLD module. Like the 1.2-μm LD module, it uses a 14-pin butterfly package filled with dry nitrogen gas and is seam welded to assure stable element operation.[13)]

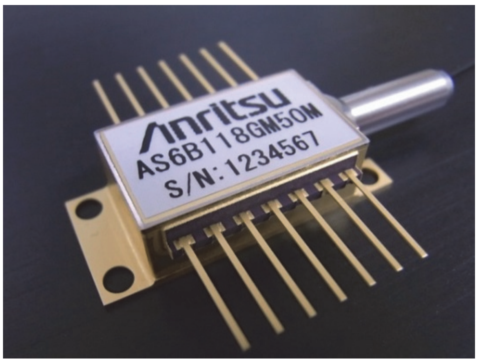

Figure 2 1.65-μm SLD Module External Appearance

The module reliability is in accordance with the Telcordia GR468-CORE standard.

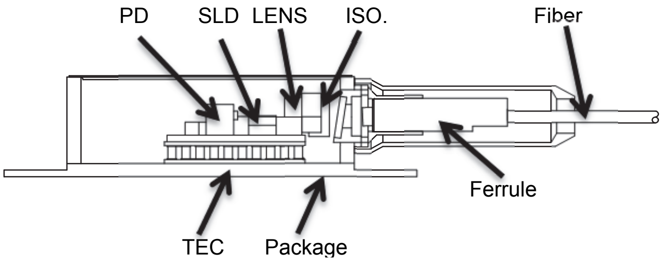

Figure 3 Module Cross-Section[14)]

Figure 3 shows a cross-section of the module. The LD, PD, and thermistor are fixed on the PC Board using lead-free solder. In addition, this board is mounted on the TEC fixed to the package in the same method.

Figure 4 shows the automatic assembly and packaging machine. Figure 5 shows the optical fiber fixing machine. The aspherical lens and optical isolator (ISO) with a reflection attenuation of 30 dB are integrated as one unit by pre-welding with a laser and fixed in position by laser welding after fiber core alignment. To suppress reflections in the light radiated from the ISO, the optical fiber input end face is polished with an angle of 8°; the ferrule is fixed by laser welding to the package. An optical fiber coupling efficiency of about 70% was obtained. Since the SLD spot is relatively flat compared to the LD, the coupling efficiency is quite poor compared to the 1.2-μm pumping LD module. The LD element is held at a constant 25°C reference operating temperature using a thermistor and TEC.

Figure 4 Assembly and Packaging Machine

Figure 5 Optical Fiber Splicing Machine

2.4 SLD Chip Structure

Figure 6 shows an image of the long-wavelength band (1.3 to 1.65 μm) SLD waveguide structure. The substrate is n-InP with an InGaAs/InGaAsP MultiQuantum Well (MQW) structure.[14)]

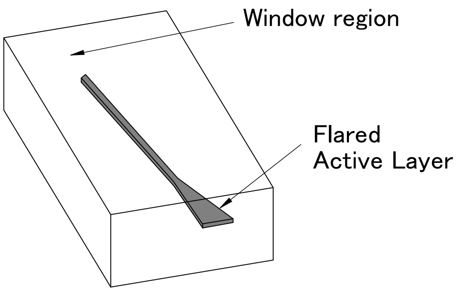

Figure 6 SLD Waveguide Image[15)]

The active layer is horizontally flared at the output (front in above figure). The waveguide uses a crossover angled structure angled at about 8° to facet formed by the cleavage.

Although the end face is AR-coated to achieve a reflection rate of 0.1%, this is insufficient from the low-reflectance standpoint. Consequently, as well as angling the waveguide so reflected light does not return to it, the flared structure is used to strengthen this effect by expanding the size of the spot in the waveguide optical horizontal plane.

In addition, reflections at the back face degrade the measurement accuracy by causing spectrum ripple. Consequently, a window region with no waveguide structure was formed between the waveguide face and the back face. Since light radiated from the waveguide face reaches facet while being dispersed by the internal crystal structure of the window region, the effect of reflections from facet is greatly suppressed.

Moreover, the element length and window region length must be optimized for the required characteristics. To achieve high output, the 1.65-μm SLD chip used in this work was fabricated with a 5-layer quantum well structure. However, since strengthening the optical confinement effect at the active layer simultaneously causes problems with increased ripple, this SLD element features a longer window region of 500 μm relative to the element length.

3 Output Characteristics

Figure 7 shows the output spectrum of the ASE TDFA forming the 1.7-μm broadband light source and of the 1.65-μm SLD module introduced here. This SLD module is driven by an injection current of 400 mA. Additionally, the 90-mW output of the 1.2-μm pumped LD was input as backward excitation to the TDFA.

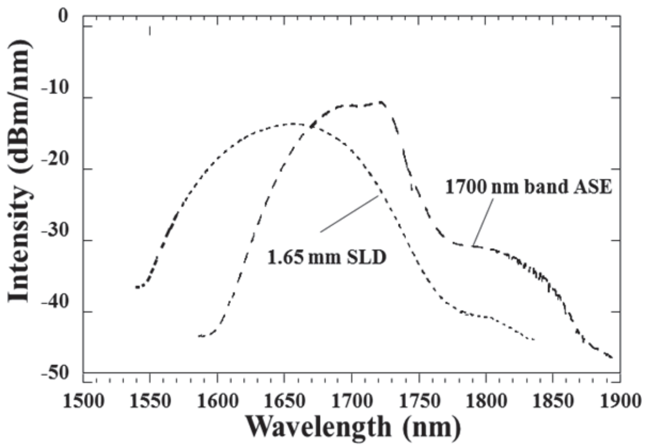

Figure 7 1.7 Broadband Light Source Output Spectrum

From Figure 7, the ASE light generated from the 1.2-μm LD pumped TDFA has a peak power close to 1.72 μm as well as a broad waveform at the long wavelength side, but the output power drops suddenly at the short wavelength side. The cascade-type spectrum of the light radiated at the same time from the 1.65-μm SLD module is shown in Figure 9. It shows a peak power close to 1.72 μm as an alternate supplementary spectrum. The waveform is quite broad on both sides of the peak. When the optical output power is standardized at −20 dBm/nm, it is clear that a wide wavelength band of about 150 nm is obtained.

4 Spectrum Evaluation System

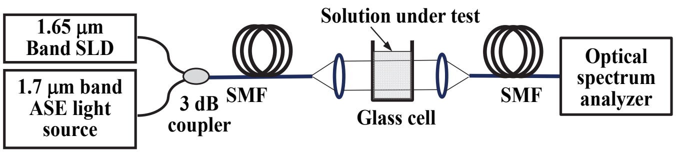

Figure 8 Spectrum Evaluation System

The optical spectroscope system is shown in Figure 8. It is composed of a glass cell for the test material (5 mm spectrum analysis of optical wavelength) positioned between fiber collimators (approx. 5-mm beam diameter and approx. 70% coupling efficiency) and an optical spectrum analyzer (adjustable measurement wavelength range of 1.2 to 2 μm).

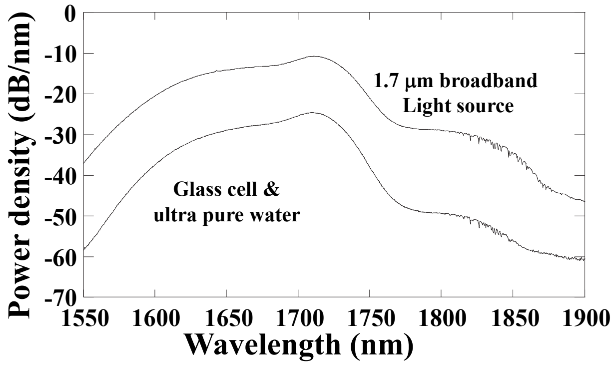

Figure 9 Glass Cell Transmission Spectrum

Figure 9 shows the transmission spectrum of the glass cell in the optical spectroscope system. When the glass cell between the optical collimators is filled with ultra-pure water, the spectrum power is degraded by about 20 dB/nm but the shape of the spectrum remains broadly the same as that of the light source.

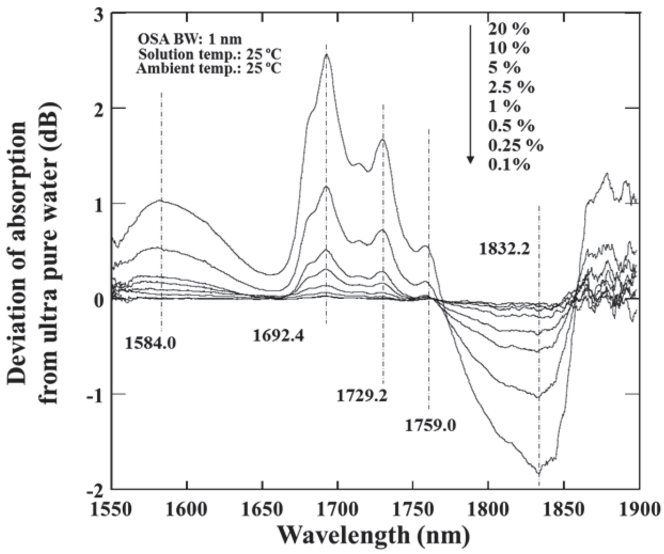

Figure 10 Optical Absorption of Aqueous Ethanol

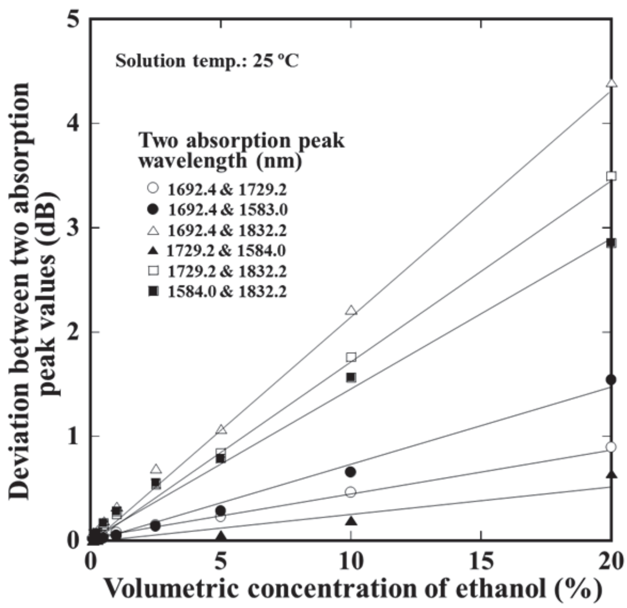

Figure 11 Aqueous Ethanol Calibration Curve

5 Rice Wine Alcohol Concentration Evaluation

5.1 Calibration Curves

Figure 10 shows the difference between the output spectra when the glass cell was filled with ultra-pure water and when it was filled with 99.99% ethanol diluted with ultra-pure water at rates from 0.1 wt% to 20 wt%. Ethanol absorption peaks are observed at 1584.0, 1692.4, 1729.2, 1759.0, and 1832.2 nm.

However, when evaluating the alcohol concentration of various types of rice wine, it is necessary to eliminate the effect of components other than alcohol. Since evaluating only absorption peaks at specific wavelengths is prone to error, we created calibration curves using peak absorption values for two wavelengths.

Figure 11 shows the calibration curves for concentrations of aqueous ethanol solutions obtained from six absorption peaks combining two out of four wavelengths. The peaks were clear at actual measurement and it was decided to create calibration curves combining the 1692.4 and 1729.2-nm wavelengths giving the best measurement sensitivity. The measurement sensitivity was 21.9%/dB.

5.2 Rice Wine Alcohol Concentration Measurement

We tested the optical spectroscope system using this light source by measuring the alcohol concentration of various Japanese rice wines (*sake*).

Figure 12 shows the absorption spectra for plum sake, *honjoshu*, unrefined sake, and pure sake. Since unrefined sake has low transmissivity, the optical power of the system was insufficient and centrifuging was required first.

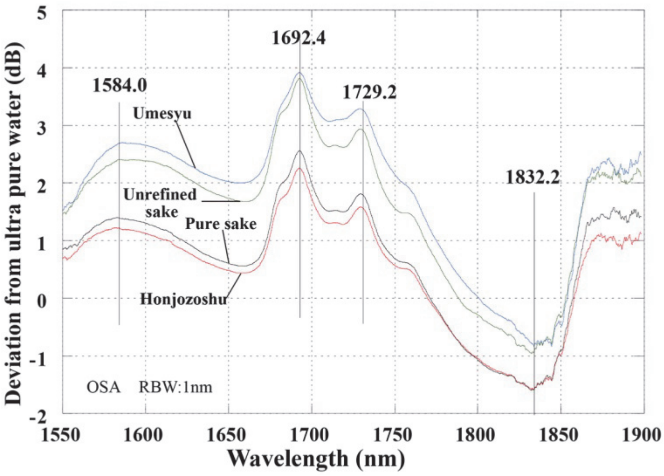

Figure 12 Deviation Spectra for Various Rice Wines

As expected, we obtained excellent optical spectrum patterns for the absorption characteristics of aqueous ethanol determined from Figure 8.

Table 1 shows the deviations of the absorption peaks for the 1692.4 and 1729.2-nm wavelengths for each type of rice wine found from Figure 12 and the estimated alcohol concentrations found from the calibration curves.

Table 1 Rice Wine Alcohol Concentrations

Sake Type	Absorption peak deviation (dB)	Alcohol concentration (%) estimated from peak deviation	Maker-indicated concentration (%)
Plum	0.6328	13.86	12.5
Honjoshu	0.6791	14.87	15.6
Pure	0.7473	16.37	17.5
Unrefined	0.8754	19.17	18.7

The indicated concentration in the above table is the concentration measured by the maker for the same test sample. The results show the biggest error (+1.4%) for the plum sake with errors of +0.5% for unrefined sake, +0.5% for honjoshu, and −1.1% for pure sake.

6 Summary

We tested a 1.7-μm broadband light source combining ASE from a TDFA pumped by a 1.2-μm FBG-LD module and a 1.65-μm band SLD module. When standardized at −20 dBm/nm, a wideband of 150 nm was obtained with a width of about 70-nm wider on the short wavelength side compared to previous ASE-only systems.

We tested this broadband light source in an optical spectroscope system for measuring the concentration of Japanese rice wines using a calibration curve for ethanol concentration. The results show a maximum error within 1.4% compared to the makers' measured values.

Since commercial single-mode fiber used for communications can be used at this wavelength band, it is possible to configure a low-cost, effective, simple, inline alcohol -measurement system for brewing production lines.

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Authors

Jun Ono
Marketing Dept.
Anritsu Devices Co., Ltd.

Hiroshi Mori
Optical Device Development Dept.
Device Development Center

Yoshiharu Shimose
Optical Device Development Dept.
Device Development Center

Tetsuya Suzuki
Optical Device Development Dept.
Device Development Center

Atsushi Yamada
Optical Device Development Dept.
Device Development Center

Kazuaki Mise
Optical Device Development Dept.
Device Development Center

Yasuaki Nagashima
Optical Device Development Dept.
Device Development Center

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