Tunable Laser Controller IC for Digital Coherent Optical Communication Systems

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The authors have successfully developed a tunable laser controller IC for digital coherent optical communication systems. The developed IC is composed of both analog and digital circuits fabricated by the CMOS (Complementary Metal Oxide Semiconductor) process, which contributes to the reduction of chip size and power dissipation. The IC, used in combination with an in-house tunable laser module, achieves even lower power dissipation by introducing switching regulators and can be implemented to small tunable assemblies, such as a micro-ITLA (Integrable Tunable Laser Assembly). This paper outlines the development of the tunable laser controller IC and its performance when used with an in-house tunable laser module.

Keywords: tunable laser, coherent, integrated circuit

1. Introduction

As data traffic is increasing, optical network equipment needs to be reduced in both size and power dissipation. In the case of digital coherent optical communication systems, which provide high speed and long haul transmission, it has been proposed that 300-pin transponders be replaced with small and low-power pluggable transceivers. The Optical Internetworking Forum (OIF) has been discussing the standardization of such coherent transceivers.

The reduction in both size and power dissipation is also needed for tunable laser assemblies used in these transceivers. Currently ITLA (Integrable Tunable Laser Assembly)[(1)], also standardized by the OIF, is widely used in 300-pin transponders, and much smaller tunable laser assemblies, such as a micro-ITLA[(2)], are anticipated to achieve small pluggable transceivers.

We have developed a tunable laser controller IC that can be implemented to small tunable laser assemblies, such as a micro-ITLA. This IC integrates optimized circuits for in-house tunable laser modules, which contributes to reducing the size and power dissipation of transceivers.

This paper outlines the development of the tunable laser controller IC and its performance when used with an in-house tunable laser module.

2. Specifications

Table 1. Target specifications for developed tunable laser assembly

Items	Target	micro-ITLA (OIF spec)
External supply voltage	+3.3 V	+3.3 V, -5.2 V,+1.8 V[1]
Power dissipation	3.5 W max.	5.0 W max.
Frequency error[*1]	+/- 1.5 GHz max.	+/- 2.5 GHz max.
Wavelength switching time	50 msec max.	10 sec max.

1: Optional

Table 1 shows target specifications for the developed tunable laser assembly. The external supply voltage is only 3.3 V, which is expected to meet the requirements for single supply operation, and targeted power dissipation is less than 3.5 W. The frequency error[*1] is within +/- 1.5 GHz, and wavelength switching time is less than 50 msec.

3. Outline of Tunable Laser Controller IC

Figure 1 shows a block diagram of a tunable laser assembly, which includes a newly developed tunable laser controller IC. The main components of this tunable laser assembly are: a tunable laser module, a central processing unit (CPU), the tunable laser controller IC, and buck converters[*2]. The tunable laser module consists of a tunable laser diode, a thermoelectric cooler (TEC), a wavelength monitor, an optical power monitor, and a temperature monitor. The CPU controls the tunable laser controller IC and provides communication interface to host devices. Most of the circuits, except for the CPU and buck converters, are integrated into the tunable laser controller IC.

The tunable laser controller IC is composed of mixed analog and digital circuits fabricated by the 0.18 μm CMOS (Complementary Metal Oxide Semiconductor) process. The basic functions of the IC are (1) to control supply voltages, (2) to control laser output power, (3) to control lasing wavelength, and (4) to communicate with the CPU. It has several drivers to supply driving current to the tunable laser diode, an ADC (Analog-to-Digital Converter) to digitize monitor voltages from the tunable laser module, three digital control blocks (supply voltage, optical power and wavelength control blocks), a PWM (Pulse Width Modulation) block, and a system controller. The supply voltage control and PWM blocks are used as high-efficient switching regulators in combination with buck converters. The switching regulators provide supply voltages to the drivers, and control voltages to the TEC for laser temperature tuning. The system controller is composed of a state-machine[*3] for semi-automatic operation, RAM (Random Access Mem-

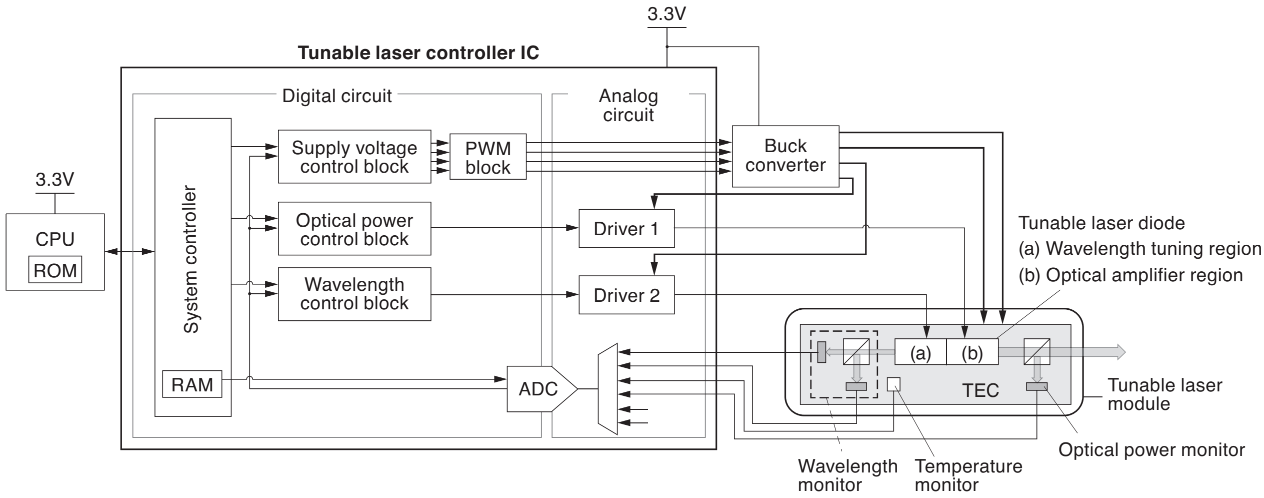

Fig. 1. Block diagram of tunable laser assembly

ory), and an SPI (Serial Peripheral Interface) interface to communicate with the CPU. The CPU stores operating laser conditions for 100 channels of wavelength in its internal ROM (Read Only Memory) beforehand. When wavelength switching from current wavelength to another wavelength is requested, the CPU sends laser operating conditions only for the next wavelength from the ROM to the RAM of the controller IC, and tunes the tunable laser diode automatically.

Hereafter we introduce the basic concept of the tunable laser controller IC: (1) reduction of power dissipation, (2) control for the tunable laser diode, and (3) reduction of wavelength switching time.

3-1 Reduction of power dissipation

The tunable laser diode and TEC dissipate most of the power in the tunable laser assembly. As shown in **Fig. 2 (a)**, total power dissipation becomes the multiplication of supply current and 3.3 V, when an external power supply of 3.3V is directly supplied to both the tunable laser diode and TEC through drivers. The total power dissipation corresponds to the total rectangular area in **Fig. 2 (a)**. The area shown as “Others” (A) is the summation of power dissipation consumed by the CPU and the tunable laser controller IC except for drivers. As for the tunable laser diode, its power dissipation is separately shown as (C) and (D) because forward bias voltage of the tunable laser diode is different for each region. Actual power dissipation that is consumed by the TEC and tunable laser diode is the area shown as (B), (C), and (D), therefore the shaded area (E) is wasted in the drivers.

In order to minimize the wasted power dissipation, switching regulators, which are composed of a supply voltage control and PWM blocks in the tunable laser controller IC and buck converters, convert 3.3 V of external voltage to any appropriate voltages with high power efficiency. Negative feed-back control loops consisting of an ADC and supply voltage control block keeps voltages constant so as to avoid voltage variation due to the change in current load of the drivers. As shown in **Fig. 1**, buck converters provide four DC voltage types. Two of them are directly supplied to both terminals of the TEC as control voltages, and the others are supplied to drivers as power supplies. The drivers are designed so as to minimize their voltage headroom. As shown in **Fig. 2 (b)**, power dissipation can be reduced to the area marked by a stair-shaped line. The areas shown as (F) and (G) indicate losses of drivers. In this configuration, the loss of buck converters (H) is added, but it is

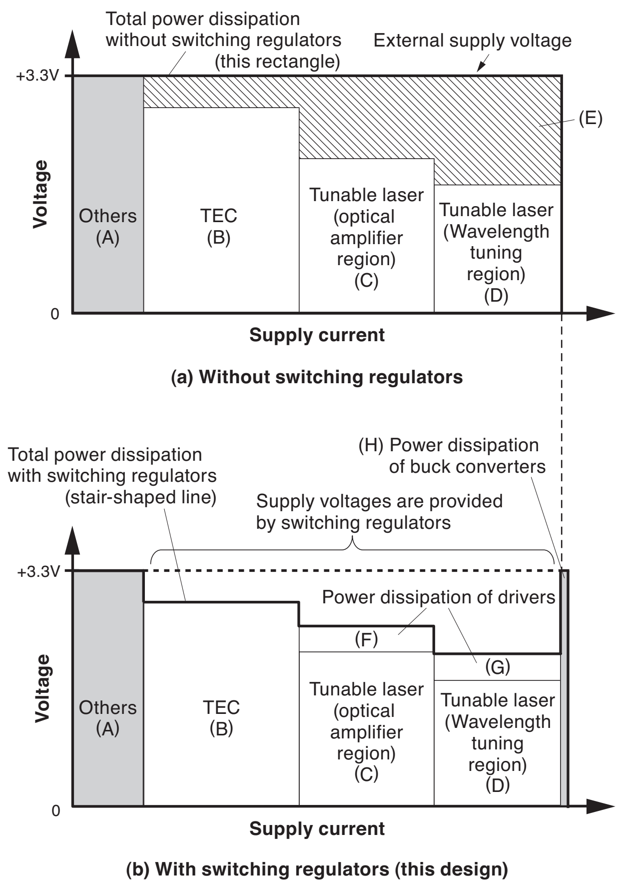

Fig. 2. Power dissipation of tunable laser assembly

smaller than the amount of the reduction of power dissipation through the introduction of switching regulators.

In general, switching regulators have high efficiency, but also have large output noise compared with linear regulators. Especially for digital coherent optical communication systems, data is transmitted by modulating optical phase and amplitude. Therefore, if this output noise is transferred to the laser driver output, it induces phase noise in a tunable laser diode output and degrades transmission characteristics. Thus, it is necessary to minimize driver output noise, i.e., to suppress not only buck converter output noise but also noise propagated from the buck converters to the drivers.

Figure 3 (a) shows waveforms of general PWM based on analog control. The input voltage is compared with a reference voltage that is saw-tooth wave, and converted to 1-bit output signal. Then the 1-bit signal is filtered to DC voltage proportional to the duty ratio of the 1-bit signal through the following buck converter.

PWM based on analog control has good characteristics because it has a continuous duty ratio, and the switching frequency can be set sufficiently. However, in this design it is necessary to implement four PWMs, and these analog circuits cannot be integrated in the IC because of the large size. On the other hand, as shown in **Fig. 3 (b)**, general PWM based on digital control has a trade-off between switching frequency and quantization error due to the discontinuous duty ratio. For instance, a 65.5 GHz oscillator is required to achieve 16-bit resolution with 1 MHz switching frequency, but this configuration consumes a lot of power.

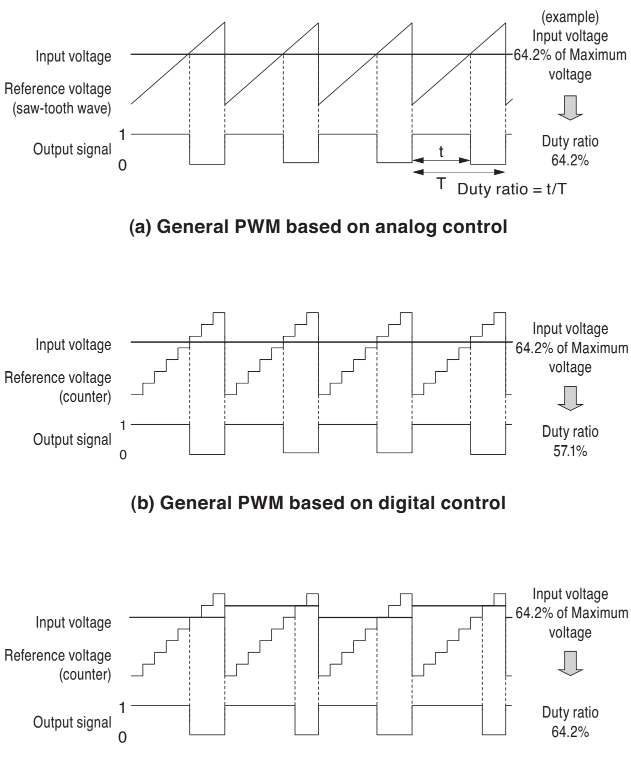

Fig. 3. PWM output waveforms

So we adopted sigma-delta modulation for digital PWM control in the tunable controller IC. As shown in **Fig. 3 (c)**, this configuration achieves higher resolution by modulating input signal in the time domain. In this configuration, a 3 to 4-bit counter can be applied for 1 MHz switching frequency; therefore required oscillator frequency is 8 to 16 MHz without any power penalty. **Figure 4 (a)** shows the calculated noise spectrum of the buck converter output. This design has 16-bit resolution and the SNR (Signal-to-Noise Ratio) is 68.3 dB with 1 MHz switching frequency.

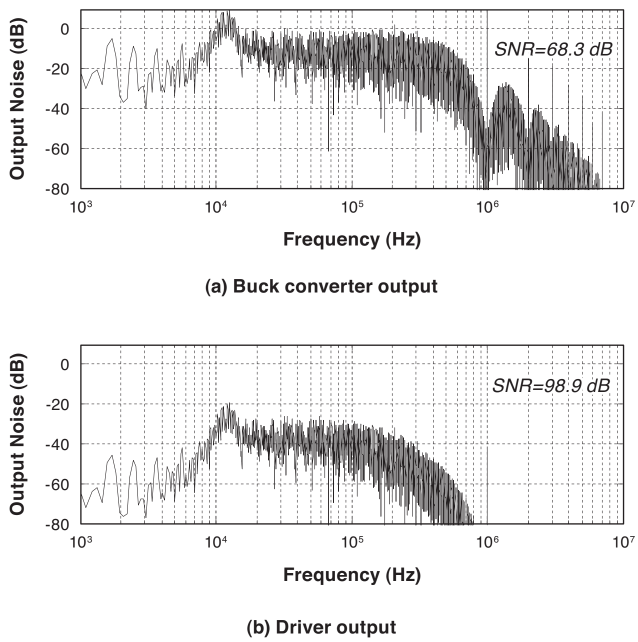

Fig. 4. Noise spectrum

We also applied another technique to suppress noise propagation from the buck converter output to the driver output. That is, we designed drivers so that they have a high power supply rejection ratio (PSRR). As shown in **Fig. 1**, two PWM outputs are supplied to the drivers as power supplies. Drivers with a high PSRR have less output noise even if there is noise in their power supply line. **Figure 4 (b)** shows the calculated noise spectrum of the driver output. Finally, this design has a superior SNR of 98.9 dB, thus the noise level is as low as that when a linear regulator is applied to the drivers.

3-2 Control for tunable laser diode

Circuits to control optical output power and wavelength of the tunable laser diode are implemented in the tunable laser controller IC. This IC (1) digitizes output voltages of the optical power monitor and the wavelength monitor by an ADC, (2) calculates errors from each target value, and (3) controls driving current to each region of the tunable laser diode so as to minimize the errors. The temperature monitor is used to keep laser temperature constant. The IC digitizes the monitor voltage by the ADC and sends it to the CPU, and then the CPU controls TEC voltages for tuning laser temperature.

The tunable laser controller IC implements these control blocks as digital circuits, which contributes to reducing both chip size and power dissipation. The number of digits for fixed-point calculation in digital circuits is optimized in terms of the trade-off between quantization noise and circuit size.

3-3 Reduction of wavelength switching time

The tunable laser controller IC has a state-machine inside, enabling semi-automatic operation for tunable laser control without suffering timing limitations due to communication with the CPU. **Figure 5** shows the diagram of the state-machine. After the IC supply voltage is settled to the proper voltage, the tunable laser controller IC sets operating laser conditions sent by the CPU, and then starts supply voltage control to supply the appropriate voltages to the TEC and drivers. After receiving a command from the CPU, it starts control of both optical output power and wavelength, and then reaches the target operating conditions. When wavelength switching from the current wavelength to another wavelength is requested, the CPU sends new operating conditions for the next wavelength and then a trigger signal for wavelength switching to the IC. The wavelength switching process can be automatically started by the trigger signal. This configuration enables fast wavelength switching without any additional transaction between the CPU and the controller IC.

Moreover, in order to achieve fast wavelength switching, the function to accelerate the response of the feedback loop is added to the IC. The response of the feedback loop by digital processing is determined by the gain of the feedback loop and sampling rate of the ADC. In this IC, fast wavelength switching is achieved by increasing the sampling rate of the ADC in the event of wavelength switching. As shown in **Fig. 6**, the IC monitors all items (A to F) by the ADC under normal operating conditions, while it monitors only items related to either optical output or wavelength (A to C) during the wavelength switching process.

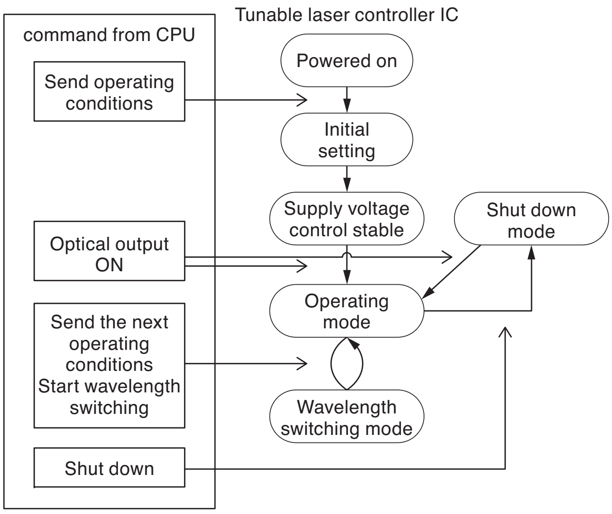

Fig. 5. Diagram of the state-machine

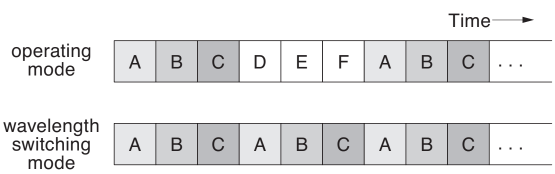

Fig. 6. Timing chart of ADC sampling

4. Characteristics

Figure 7 shows the power dissipation of the tunable laser assembly when we use the controller IC. The power dissipation is 4.0 W in the case of the conventional configuration without switching regulators, whereas it is 3.4 W for the newly developed solution with switching regulators. The tunable laser controller IC satisfies the target (≤ 3.5 W).

Figure 8 shows the output waveforms of the buck converter and the driver. The output noise of the buck converter is suppressed to around 10 mV. The output noise of the driver is as low as 3 mV and might mainly come from the background, because there is no correlation with the

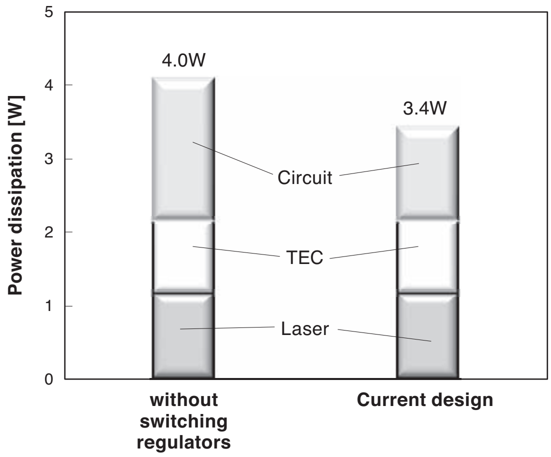

Fig. 7. Power dissipation

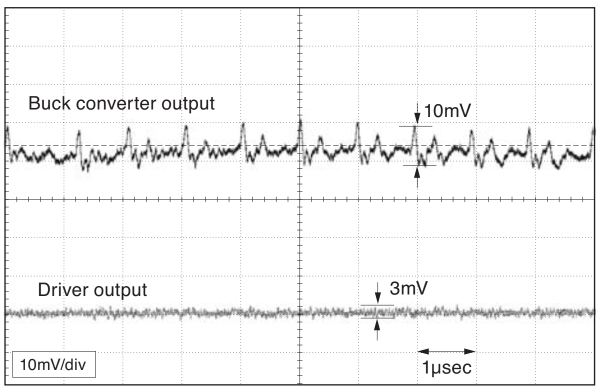

Fig. 8. Output waveforms

buck converter output noise. These results indicate that drivers with a high PSRR contribute to reducing noise transfer from switching regulators to the tunable laser diode.

Figure 9 shows the measured and simulated results of how the 12 GHz frequency error converges to the target value when the IC starts wavelength control at T = 0. Both results match very well, and the convergence time is less than 5 msec. The frequency error after convergence is very small compared to the target specification of within +/-1.5 GHz.

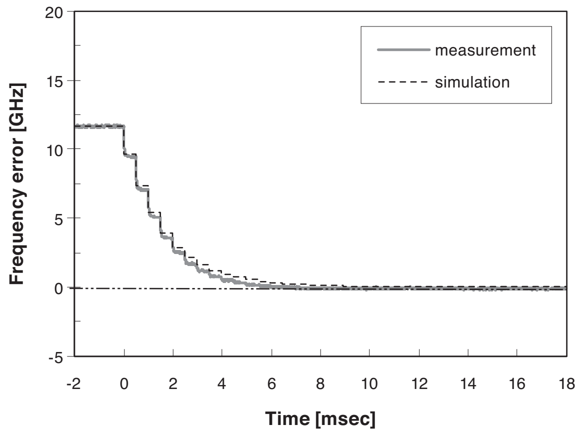

Fig. 9. Wavelength response

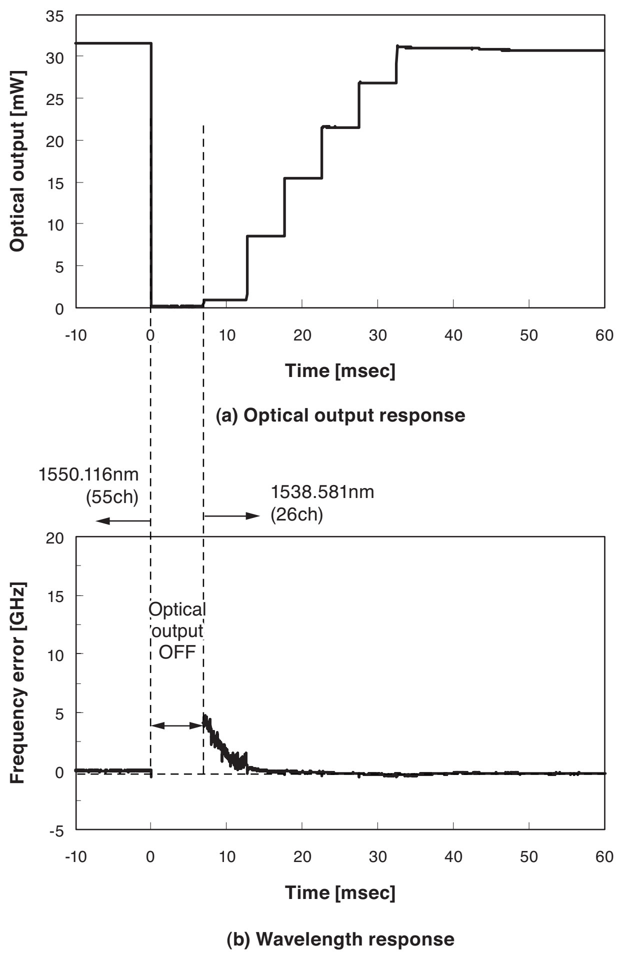

Fig. 10. Wavelength switching response

Figure 10 shows a response of optical output power and wavelength, when wavelength switching is requested. The tunable laser diode is shut off instantly after receiving new operating conditions for the next wavelength (26ch, 1538.581nm) from the CPU, and then optical output power is gradually increased to the appropriate value. Both optical output power and wavelength are close to each target value, within 50 msec. This result is one example of wavelength switching, and the turn-on slope of the optical output power and wavelength switching time are both adjustable by changing the state-machine parameters.

Photo 1 shows a photograph of the tunable laser controller IC. The size of the external dimension is 5 × 5 mm^2. **Table 2** shows the specifications for the tunable laser controller IC.

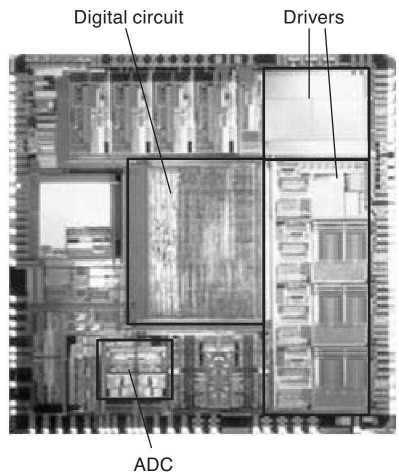

Photo 1. Chip photograph of tunable laser controller IC

Table 2. Specifications for tunable laser controller IC

Supply voltage	+3.3 V +/- 7%
Chip size	5 mm × 5 mm
Package size	7 mm × 7 mm
Package type	56 pin-QFN
Number of gate	880 k gates
Power dissipation (except for drivers)	49 mA

5. Conclusion

We have developed a tunable laser controller IC intended for small tunable laser assemblies. The IC, used in combination with the in-house tunable laser module, achieves low power dissipation by introducing switching regulators and can be implemented to small tunable assemblies, such as a micro-ITLA, which can be applied to next generation transceivers for digital coherent optical communication systems.

Technical Terms

*1 Frequency error: The relation between wavelength and frequency is expressed by the equation as below : Frequency [Hz] = (speed of light [m/s]) / wavelength [m]. 1.5 GHz of frequency error corresponds to about 12 pm of wavelength error.

*2 Buck converter: Step-down converter. This circuit outputs a voltage proportional to the duty ratio of an input signal with high power efficiency.

*3 State-machine: Sequential logic circuit to generate control signals. The next status is determined by both the input condition and current status.

References

(1) OIF-ITLA-MSA-01.2, "Integrable Tunable Laser Assembly MSA"

(2) OIF-Micro-ITLA-01.0, "Micro Integrable Tunable Laser Assembly Implementation Agreement"

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