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Automated Power Control for Mobile Laser Speckle Imaging System

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Abstract

Recently, Laser Speckle Imaging (LSI) has been applied to measure blood perfusion in human skin. Attractive features of LSI are its temporal resolution and relatively simple instrumentation. The progressive reduction in the cost and size of camera technology now enables development of mobile LSI instrumentation. To reduce the size of LSI to a mobile platform, we are faced with new challenges in terms of reducing power consumption and heat without sacrificing detection accuracy. To address these challenges, we propose pulsed laser operation using a new automated power control (APC) circuit. By synchronizing the pulses to the laser diode driver with the camera shutter, the camera detects a similar raw speckle image as before while consuming only a small fraction of the power. Furthermore, the reduced power consumption in turn keeps the temperature of the case low, increasing the stability of the system. We validated our solution using simulations in Pspice, and we evaluated the operation of the circuit using a prototype APC board and a commercial camera.

Keywords

Automated Power Control; Low Power; Pulsed Operation; Handheld Device; Embedded System; Laser Doppler Flowmetry

I. Introduction

For mobile devices, power consumption is one of the most important factors describing system performance. Although the energy density of lithium-ion batteries has been increasing, the size and weight of these batteries limit their utility in mobile devices. Furthermore, precise control of laser diodes in mobile devices poses a significant challenge. A typical laser diode (i.e., Sanyo DL6147-040, 635 nm center wavelength) has an average power consumption of 156 mW, which is approximately 40% of the power consumption of the entire device.

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Generally, the laser diode current required to emit a specified optical power is proportional to the case temperature of the diode. As the laser diode temperature increases, it requires a proportionally higher current to sustain the optical power. In the absence of cooling, the laser diode will eventually cease to function due to overheating. Furthermore, the optical wavelength is temperature dependent, and an increase in case temperature will result in a shift in center wavelength. In this letter, we present a method to achieve pulsed mode operation of the Automated Power Circuit (APC) for the driving circuit of the laser diode. With this method, we are able to reduce the power consumption of the diode and enable its stability. We describe an application of this method for characterization of fluid flow in an in vitro biological tissue phantom.

Fig. 1 is the brief blockdiagram of mLSI (Mobile Laser Speckle Imaging) system. The main controller (SoC) takes charge of operating the camera and APC circuit and the display (LCD). The SoC can set the output power of the laser diode using GPIO interface connected to the circuit. The pulse required to operate the circuit is fed by the camera using the external sync signal, which is synchronized with its shutter. APC circuit provides laser light to take images using the camera. Raw speckle images acquired by the camera is transferred to the memory (SDRAM). The processing core processes the image data and displays the data on LCD.

II. Solution

Our design goal is to sustain laser diode performance for 5 minutes. As described above, the case temperature and the optical power of the laser diode must be stabilized. We now describe an approach to addressing each of these design issues.

To control the case temperature, we have identified two potential solutions. First, a thermo-electric cooler (TEC) can be used to transfer thermal energy from the laser diode to an attached heat sink. In order to integrate TEC into a mobile device, two key problems are the non-negligible size of TEC and the additional power to operate TEC. Hence, we selected an alternate solution: pulsed operation mode of the laser diode while sustaining the output power of the laser intensity using APC.

APC (Fig. 2) is a feedback circuit to control the current passing through the MOSFET (M1) by comparing the monitoring current from the laser diode with the preset value of the potentiometer (U8). The SoC in Fig. 1 sets the resistance value of this potentiometer based on the information to get images: distance from the object, f-stop number of the camera, and exposure time of the camera. The circuit is triggered by the signal synchronized with the shutter of the camera. So, the duty ratio is dependent on the frame rate and the exposure time of the camera. For example, 10ms exposure time and 30fps frame rate – common exposure time for LSI application and desired frame rate for mobile LSI system – give us a duty ratio of 30%, which allows the diode to cool down for 700ms per second.

To control the output power of the laser diode, the APC measures the monitoring current from the diode. The laser diode (D3) is composed of two diodes: a laser diode and a monitoring diode. The monitoring diode is a photo diode whose current flow is proportional to the output power of the laser diode. The monitoring current can be compared with the output power of the preset output value stored in potentiometer U8.

Since the voltage difference between the two other pins of the zener diode (D4) is maintained at 3.0 V, the divided voltage output from the `W' of U8 can be easily controlled. The OPAMP (U7) is in charge of amplifying the difference between the preset value (by U8) and the monitored value (from U6) to control the current flowing through the MOSFET (M1). To control the current precisely, the differential amp made from U7 has the gain of R12/R2 (where

R2=R4 and R12=R5), on the order of 2–3. Since the difference is inversely proportional to the current, we can make a negative feedback loop with this circuit.

Two latencies are introduced by the pulsed operation mode: (1) circuit response time to the pulse source, and (2) the turn-on delay of laser diode. Once the pulsed stimulus is introduced to the circuit, the OPAMP compares the values of the preset voltage of the potentiometer and the monitor current output from the laser diode, and drives the switch to turn on the laser diode. The time required for the circuit to drive the switch is the *circuit response time*. After the switch is turned on, the laser diode needs time to turn on and emit light. We call this time period the *diode response time* τ_d.

According to laser diode modulation theory, the turn-on delay τ_d is a function of the carrier life time τ_e of the semiconductor, the bias current of the laser diode, and the driving current. If the bias current is below the threshold level I_{th}, then the turn-on delay τ_d of the laser diode is given by the following equation [1]:

$$\tau_d = \tau_e \ln \frac{I_{\text{on}} - I_{\text{off}}}{I_{\text{on}} - I_{\text{th}}} \tag{1}$$

where I_{on} and I_{off} are the *turn-on current* and *turn-off current* of the diode, respectively, and I_{th} is the *threshold current* of the diode.

The carrier life time τ_e of Al Ga In P, the semiconductor material used for Sanyo DL-6147-040 is on the order of a few nanoseconds [2]. The typical operating current of the laser diode at output power of 40 mW is 65 mA, and the typical threshold current of the diode is 30 mA. This means τ_d is about 1.4 times the carrier life time, if the bias current of the diode was set at 0 mA. The turn-on delay of the laser diode will be around a few nanoseconds, which is less than 0.001% of 0.1ms, the shortest exposure time of our system. Therefore, the effect of the turn-on delay is negligible for the purpose of our application. Therefore, in the simulation, we have replaced the laser diode with a simplified model composed of a current-controlled current source and a diode. Since we are only concerned about the circuit latency introduced by the APC using pulsed operation mode, we decided to make use of this substitute model for our simulation without sacrificing accuracy.

During the simulation, the independent variables were the camera exposure time, frequency of the pulse, and the potentiometer value. We have examined the response time of the circuit (τ_c) and power consumption according to the variables.

Our simulation results suggest that the latency τ_c introduced by the circuit is independent of the exposure time or duty ratio of the pulse. The latency is fixed to certain value (207 ns) for various pulse frequencies from 10–50 Hz corresponding the frame rate of images from 10–50 fps. Moreover, the contribution of the latency to the total camera exposure time is negligible even for 0.1 ms of exposure time (0.207%, compared to the total integration time). The settling time is measured when the drain current of the MOSFET (M1, Fig. 2) reaches the 2% boundary of the saturation value. The drain current is set to 55 mA, which can drive 30 mW output power from the laser diode under room temperature.

To control the optical power, the forward current of the diode must be controlled. However, manipulation of the current may introduce a non-negligible latency. The operating parameters of the laser diode are listed in Table I. We varied the operating current of the diode between 40 mA to 70 mA, resulting in the necessary forward current to enable an optical power ranging between 12 mW and 40 mW. The frequency of the pulse was set to 50 Hz and the exposure time to 0.1 ms, to simulate a worst-case scenario. Since the potentiometer value changes the

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input voltage of U7 (Fig. 2), the latency is closely related to the potentiometer value. However, the maximum latency introduced by the operation is only 0.303% of the total integration time (Fig. 3(b)). Hence, the latency introduced by modulating the forward current is negligible.

III. Evaluation

To test the performance of our pulsed laser diode circuit, flow characterization in an in-vitro biological tissue phantom was performed. The silicone phantom contains TiO_2 scattering particles to mimic the optical properties of skin tissue. A tube was embedded on the surface of the phantom. We used an infusion pump to induce flow of a 20% solution of intravenous fat emulsion (Liposyn II, Abbott Laboratoies) solution through the tube. Laser speckle imaging (LSI) was used to acquire images, which were analyzed to estimate the relative fluid flow speed [7].

Briefly, LSI involves analysis of coherent light remitted from an object [4]. The use of coherent illumination results in a grainy speckle reflectance pattern that is due to interference effects. Raw speckle reflectance images are converted to maps of local speckle contrast and ultimately to speckle flow index (SFI) maps, which quantify the degree of relative motion of scattering particles. The relationship between the speckle contrast and the flow speed is described by the following equation (2):

$$C=\sqrt{\frac{1}{SFI\cdot T}} \tag{2}$$

where *C* is the speckle contrast, *SFI* stands for Speckle Flow Index and *T* is the exposure time of camera [5]–[7].

We hypothesized that the flow values are comparable between the use of a pulsed laser diode operation mode and a continuous laser diode operation mode. The pulsed mode would result in less power consumption than continuous mode. To test this hypothesis, we used 1) a commercial monochrome CCD camera (Retiga 2000R), which was synchronized to the APC to acquire raw speckle reflectance images, 2) the prototype APC to control the laser diode, 3) the thermistor to measure the case temperature of the laser diode, and 4) the silicone phantom (Fig. 4). To measure the temperature of the laser diode, NTC thermistor (MC65f103) from General Electric was attached to the bottom of the laser diode case (Fig. 4). The changes of temperature were measured with a digital multimeter, and the values were converted using the table provided by the manufacturer of the thermistor [8]. We measured the temperature every 10 seconds for five minutes.

To evaluate the Pulsed Operation mode (PO mode), we compare it with the Always-on Operation mode (AO mode). AO mode means the laser diode is kept turned on. The power consumption of the circuit shows consistency with the simulation result (Fig. 5(a)). Excluding the standby current for the rest of the circuit, the power consumption of PO mode is 38% that of AO mode, which is consistent with the duty ratio of 0.34 for the camera integration pulse. The frame rate is 34 fps, and the camera integration time is 10 ms.

In the PO mode, the case temperature converges to 24°C after 3 minutes. In the AO mode, the case temperature reaches to continues 24°C after 3 minutes and keeps increasing. Since the wavelength of the laser diode depends on its temperature, we have referenced the product specification of the laser diode to determine the expected wavelength change according to the temperature [3]. Based on this analysis, we estimated a wavelength change in AO mode to be over 1.5 nm, as compared to 0.37 nm in PO mode..

Since the changes in wavelength are related to the coherence length of the laser diode, we anticipate that such a change would modulate the LSI data with prolonged usage. Hence, for application of our laser diode in LSI, it is important to stabilize the temperature of the laser diode.

To study the LSI data in PO and AO modes, we collected raw speckle image data in both modes. Qualitatively, the raw images and flow maps appear similar (Fig. 6). Quantitatively, both PO and AO modes result in similar SFI data using image exposure times between 5 and 20 ms (Fig. 7). For the data presented in Fig. 7(a), the camera exposure time was 10 ms. For the data presented in Fig. 7(b), the flow rate in the tube was 2 mm/sec. The fluid inside the tube was based off Lyposyn II 20% solution, a scattering liquid used frequently as a blood surrogate [6].

IV. Conclusions

To integrate a coherent light source into a mobile device, we engineered a pulsed laser diode circuit. Collectively, our data demonstrate that using our APC to collect LSI data is equivalent to using continuous-wave operation, but with the advantages of 38% lower power consumption. The APC shows high stability of the laser wavelength and coherence length. We envision that our circuit design is applicable to mobile devices with an integrated coherent light source.

Acknowledgments

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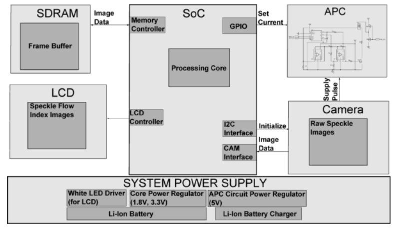

Fig 1.
mLSI Blockdiagram.

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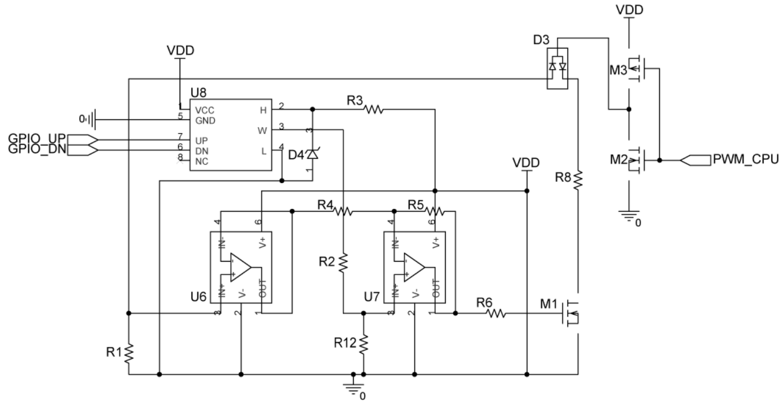

Fig 2.
Schematic of APC.

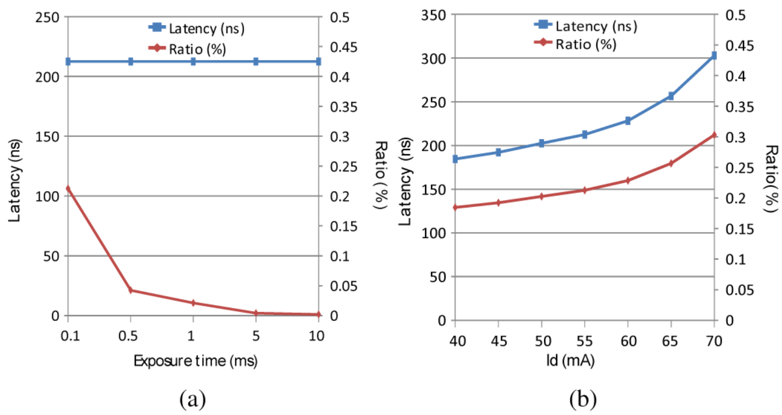

Fig 3.

Latency analysis using the simulation: (a) Latency according to the exposure time, (b) Latency according to the potentiometer value

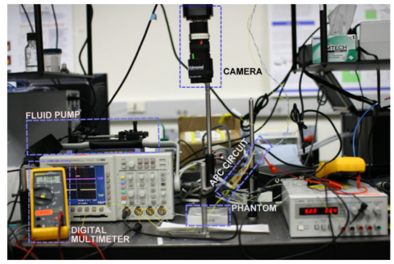

Fig 4.
Experimental setup for APC evaluation

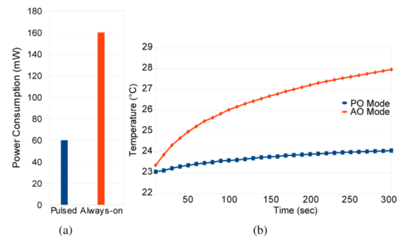

Fig 5.

Evaluation result: (a) Power consumption comparison of AO mode and PO mode, (b) Temperature change of AO mode and PO mode

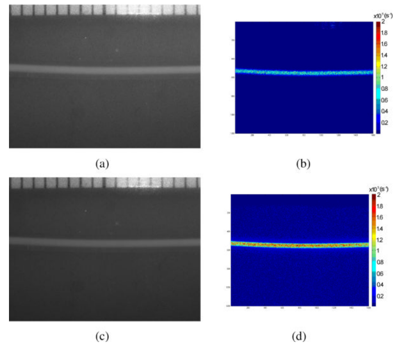

Fig 6.

Raw images and SFI map from AO mode and PO mode for 10 ms exposure time: (a)Raw image of AO mode, (b)SFI map of AO mode, (c)Raw image of PO mode, (d)SFI map of PO mode

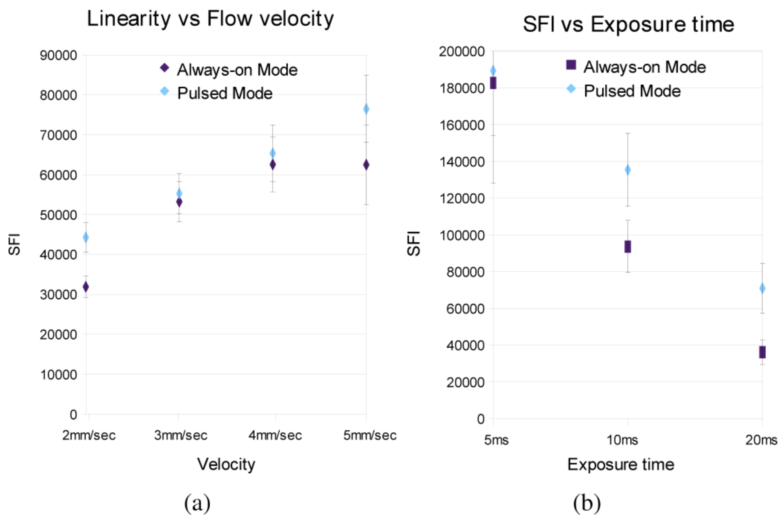

Fig 7.

SFI values acquired using the APC: (a) SFI values for various flow rate in the tube on the phantom, (b) SFI values for various exposure time of the camera

TABLE I

Threshold and operating current of DL-6147-040 [3].

Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Threshold Current	I_{th}	CW	.	30	50	mA
Operating Current	I_{op}	P_o = 40mW	.	65	85	mA