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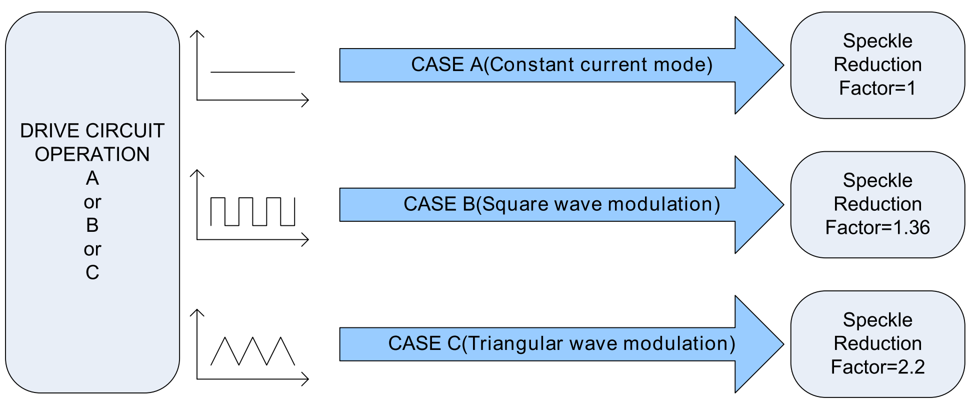

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Implementation of a Current Drive Modulator for Effective Speckle Suppression in a Laser Projection System

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Abstract: We report on the implementation of a current drive modulation circuitry that is effective in suppressing speckle noise for laser diodes. The drive circuit allows for operating the laser diode current at constant dc or modulating the current with square or triangular wave signals. We theoretically investigate the speckle reduction factors that correspond to the different modes of operation. The theory predicts that triangular wave modulation gives the highest speckle reduction ratio. This means that when used as a projector, the laser should be fed with triangular modulated current for the most effective speckle suppression. We then verified the theoretical results by experimental measurements. We demonstrated effective speckle noise suppression by implementing a drive current modulator.

Index Terms: Speckle, speckle reduction, laser current modulation.

1. Introduction

Display systems that employ lasers enable humans to see potentially 90% of the color spectrum that humans can perceive, whereas without lasers, they can only display around 40% of the color gamut [1]. In addition to having a wide color gamut, laser light preserves its output power for a very long time (up to 25000 hours). The laser preserves its quality (such as color saturation and luminance) during its lifetime [2]. Moreover it is also possible to display 3-D stereoscopic images using lasers [3]. All these properties make laser an ideal light source for display and projection applications [4]–[6].

The main disadvantage of laser light is the speckle phenomenon that creates noise, which degrades the image quality. Since all imaging systems that employ lasers suffer from speckle noise, it is crucial to combat it [7]–[10]. Until now, several methods have been utilized to successfully solve the speckle noise problem [11]–[13]. In this paper, we demonstrate the implementation of a current drive modulator for effective speckle suppression in a laser projection system. We first introduce the modulation circuit and then report on the speckle suppression results.

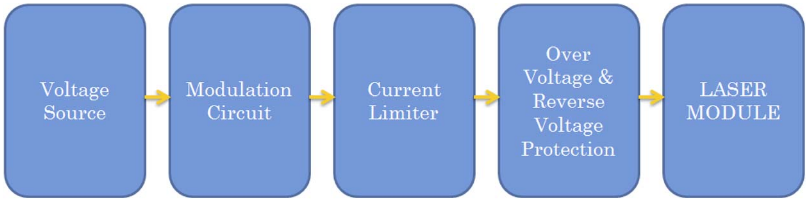

Fig. 1. Block diagram of the laser drive circuit.

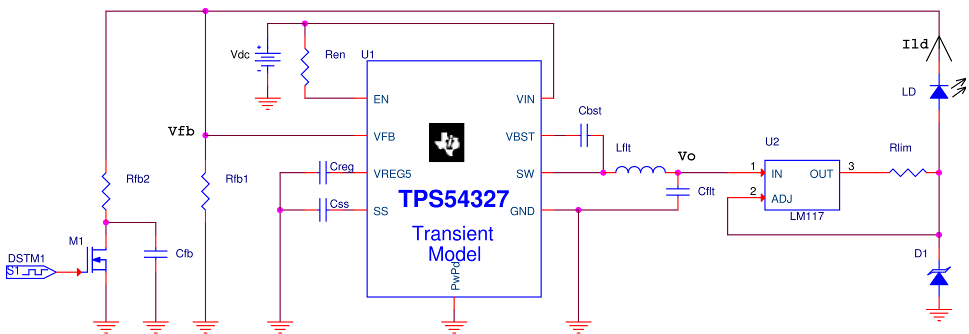

Fig. 2. Schematic of laser diode driver.

2. Method

The block diagram of the drive circuit based on current control is given in Fig. 1, and the schematic is given in Fig. 2. Our laser drive circuit is composed from 5 parts. The first part is the voltage source which provides dc supply voltage V_{dc}. For the modulation circuit $U1$ and its peripheral components, R_{en}, C_{reg}, C_{ss}, C_{bst}, L_{flt}, and C_{flt} are used. Output of the modulation circuit is denoted by V_o. R_{fb1}, R_{fb2}, C_{fb}, $M1$, and $DSTM1$ are used as part of the modulation circuit and they determine the shape and level of the laser diode current. $U2$ and $R_{\lim}$ are used to limit the current. $D1$ protects the circuit from overvoltage and reverse voltages. The final part of the block diagram is the laser module which is denoted by LD in the circuit schematic. The laser diode emits visible light centered around a wavelength of 637 nm.

The output voltage of the regulator (V_o) is related to the laser diode current (I_{ld}).

LM117 Integrated circuit $(U2)$ and the limiting resistor $R_{\lim}(\Omega)$ are used to limit the maximum allowed current of the laser diode. $I_{\lim}(\mathrm{A})$ denotes the limiting current and is calculated by the following formula: $I_{\lim} = 1.25/R_{\lim}$, and the limiting current is adjusted to the 100 mA level.

In this project, current control method used, since it enabled the direct modulation of the diode current. The laser current was kept constant at a DC value, modulated with a square wave (switched on-off), or modulated with a triangular wave continuously.

Three modes of operation can be achieved using this circuit as follows:

2.1. Constant Current Mode

In order to operate the circuit at constant current mode (drive current at dc value) it is necessary to connect the gate of M1 to ground. In this mode of operation, the direct current is given by $I_{ld} = I_{dc} = V_{fb}/R_{fb1}$. $U1$ step down converter feedback input V_{fb} is kept at 0,765 V so I_{ld} can be tuned easily by changing R_{fb1}.

2.2. Square Wave Modulation

If a square wave is applied by the $DSTM1$ to the gate of M1 while C_{fb} is disconnected, then the laser diode current is modulated in a square wave form. The maximum value of the current is determined by: $I_{\text{high}} = V_{fb}/(R_{fb1}//R_{fb2})$. And the minimum value of the current is given by

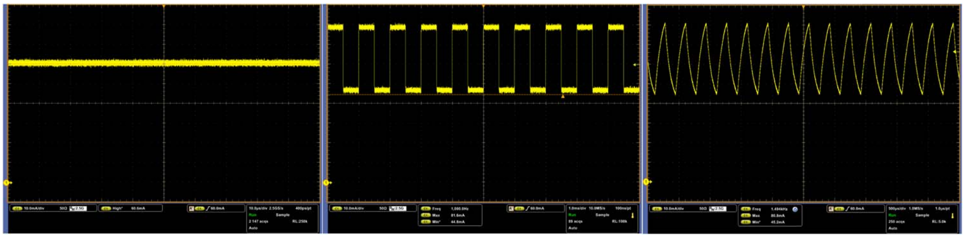

Fig. 3. (a) DC current. (b) Square wave current. (c) Triangular wave current.

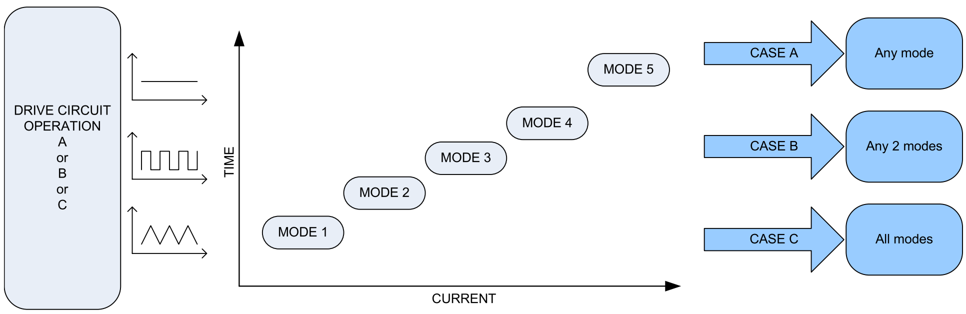

Fig. 4. Mode selection depending on current modulation.

$I_{\text{low}} = V_{fb}/(R_{fb1})$. The frequency of the modulated current waveform is equal to the frequency of the square wave applied to the M1 gate.

2.3. Triangular Wave Modulation

If a square wave is applied to the gate of M1 with *DSTM*1 while C_{fb} is connected, then the laser diode current is modulated in the triangular shaped wave form. The slope of the wave can be adjusted by C_{fb}. The maximum and minimum value of the drive current are determined in the same way as with the square modulation $I_{\text{high}} = V_{fb}/(R_{fb1}//R_{fb2})$ and $I_{\text{low}} = V_{fb}/(R_{fb1})$.

3. Theoretical Analysis and Results

By using the drive circuit the laser diode was driven by the different modulation signals (dc, square wave, triangular wave), as shown in Fig. 3. The laser diode was characterized using a spectrometer. It was found that the laser diode had five independent longitudinal lasing modes in the 40–85 mA drive current range, as shown in Fig. 4.

In the constant dc current drive mode, a single image will be created that arises from the corresponding longitudinal mode (see case A in Fig. 4). In the square wave drive current modulation(see case B in Fig. 4), the output will be the superposition of two independent speckle patterns that are created by the mode corresponding to the minimum current value and the mode corresponding to the maximum drive current. In the triangular wave modulation case all the modes that reside between the maxima and minima will be excited and superimposed, as shown by case C in Fig. 4.

We will theoretically calculate the expected speckle suppression that corresponds to the three modes of operation. Speckle is quantified by the speckle contrast and is mathematically calculated by the following expression [14], where σ denotes standard deviation and $\bar{I}$ denotes mean value of the picture:

$$C = \frac{\sigma}{\bar{I}}. \tag{1}$$

In order to quantify the performance of the modulation, we use the speckle reduction factor (R) given by [15], [16]

$$R = \frac{C_i}{C_f} \tag{2}$$

where C_i and C_f denote the initial and final speckle contrasts, respectively. The speckle contrast is theoretically calculated by the following expression:

$$R = \frac{\sum_{n=1}^{N} \overline{I_n}}{\sqrt{\sum_{n=1}^{N} (\overline{I_n})^2}}. \tag{3}$$

In this formula, the speckle reduction formula R is calculated by taking into account n, the number of the different excited modes, and I_n their relative intensities, which is proportional to the current passing through the laser diode.

Based on the speckle relations (3), we now theoretically estimate the speckle reduction factor for each mode of operation of the presented drive circuit, as given by modes A, B, C in Fig. 4.

We now calculate the speckle reduction factor that correspond to the three different modes of operation of the drive circuitry.

3.1. Case A: Constant Current Mode

For each current value, the reduction factor is

$$R = \frac{\overline{I_n}}{\sqrt{(\overline{I_n})^2}} = 1 \tag{4}$$

for all I_n. In the case where the circuit drives the laser diode with constant current the output image consists of one mode, and therefore, the speckle reduction factor is unity. No matter what the dc drive current is, the speckle reduction factor will be equal to 1 for all.

3.2. Case B: Square Wave Modulation

When the drive current modulation is made a square wave the output modes will depend on the drive currents minima and maxima. The circuit components were chosen such that the modulation occurs between 45 and 80 mA. The output in this case will be the superposed image of speckle mode 1 and mode 5. The theoretical expectation of speckle reduction can be calculated using

$$R = \frac{45 + 80}{\sqrt{(45)^2 + (80)^2}} = 1.36. \tag{5}$$

The ideal theoretical limit for the speckle reduction factor for two modes is $\sqrt{(2)} \approx 1.41$.

3.3. Case C: Triangular Wave Modulation

In the case where the modulation is applied continuously as a triangular function the output will consist of the superposition of the corresponding excited modes. The functions maxima and minima are kept the same as with the square wave modulation such that the output consist of the superposition of the modes (1, 2, 3, 4, and 5). It is evident that the number of superposed modes have increased in comparison to the square wave modulation. When five independent modes are superposed, the speckle reduction factor could be ideally as high as $\sqrt{(5)} \approx 2.24$. In order to have an effective speckle reduction factor, it is therefore necessary to superpose as

TABLE 1

Speckle reduction factors

	R theory	R measurement
Case A(dc current)	1	1
Case B(square modulation)	1.36	1.32 ± 0.01
Case C(triangle modulation)	2.2	2.16 ± 0.01

many independent modes as possible. The theoretical speckle reduction factor for this modulation range can be calculated using

$$R = \frac{45 + 55 + 62 + 70 + 80}{\sqrt{(45)^2 + (55)^2 + (62)^2 + (70)^2 + (80)^2}} = 2.2. \tag{6}$$

Note that this speckle reduction factor of $R = 2.2$ is very close to the optimum ideal speckle reduction factor for five superimposed modes $R \approx 2.24$.

The results are summarized in Table 1.

In order to verify our theoretical predictions we performed an experimental study with the laser projection system. We projected the laser beam onto a screen placed at a 40 cm distance. We characterized the speckle pattern with a camera that was located 20 cm away from the reflection surface. The integration time of the camera was made 20 ms, which is close to the human eyes temporal integration time [17]. In the different modes of operation, images were taken by the camera. These images were then analyzed by computer software, by which the speckle reduction ratios were determined. The experimentally measured results are summarized together with the theoretical expectations in Table 1. The modulation frequency depends on the integration time of the camera. Since 20 ms corresponded to 50 Hz, we chose 500 Hz as our starting modulation frequency in order to have a sufficient bandwidth and averaging. Of course, one could change the camera integration time and take measurements at different frequency ranges.

4. Conclusion

In this paper, a drive circuit scheme is presented that allows driving the current of a laser diode in constant dc, square wave, or triangular waveform modes. For a laser diode used as a projector, we analyze the output modes and theoretically calculate the expected speckle noise reduction factors that correspond to the specific drive current mode. The theoretical model predicts that the maximum speckle noise reduction factor will occur when the laser diode is driven in triangular modulation. We then used a laser source as a projector and characterized its speckle noise for the different modes of operation. The experimental measurements are in good agreement with the theoretical model. We have successfully implemented a current drive modulator for effective speckle suppression in a laser projection system.

References

[1] S. Morgenstern, "Laser-sharp colors," *Popular Sci.*, vol. 270, no. 1, p. 24, Jan. 2007.
[2] G. Hollemann *et al.,* "RGB lasers for laser projection displays," in *Proc. Electron. Imag.*, 2000, pp. 140–151.
[3] I. M. Koba, "High-Resolution Spatial Light Modulator for 3-Dimensional Holographic Display," U.S. Patent 6819469 B1, Nov. 16, 2004.
[4] K. V. Chellappan, E. Erden, and H. Urey, "Laser-based displays: A review," *Appl. Opt.*, vol. 49, no. 25, pp. F79–F98, Sep. 2010.
[5] I. Fujieda, T. Kosugi, and Y. Inaba, "Speckle noise evaluation and reduction of an edge-lit backlight system utilizing laser diodes and an optical fiber," *J. Display Technol.*, vol. 5, no. 11, pp. 414–417, Nov. 2009.
[6] G. Zheng *et al.,* "Laser digital cinema projector," *J. Display Technol.*, vol. 4, no. 3, pp. 314–318, Sep. 2008.

[7] M. S. Brennesholtz, "56. 4: Invited paper: New-technology light sources for projection displays," in *Proc. SID Symp. Dig. Tech. Papers*, 2008, vol. 39, no. 1, pp. 858–861.
[8] A. Rafiee, M. H. Moradi, and M. R. Farzaneh, "Novel genetic-neuro-fuzzy filter for speckle reduction from sonography images," *J. Digit. Imag.*, vol. 17, no. 4, pp. 292–300, Dec. 2004.
[9] L. Liren, "Structure and operating mode of synthetic aperture laser imaging ladar for speckle reduction [j]," *Acta Optica Sinica*, vol. 10, p. 045, 2011.
[10] C.-Y. Chen *et al.,* "Reduction of speckles and distortion in projection system by using a rotating diffuser," *Opt. Rev.*, vol. 19, no. 6, pp. 440–443, Nov. 2012.
[11] L. Hao *et al.,* "Speckle suppression in laser display," *Laser Infrared*, vol. 36, no. 10, pp. 927–930, 2006.
[12] X. Li *et al.,* "Speckle contrast reduction in laser display," *Chin. J. Liquid Crystals Displays*, vol. 23, no. 2, pp. 153–154, 2008.
[13] M. Xu, W. Gao, Y. Shi, H. Wang, and B. Du, "Laser speckle suppression due to dynamic multiple scattering scheme introduced by oblique incidence," *Spectroscopy Spectral Anal.*, vol. 34, no. 6, pp. 1716–1721, Jun. 2014.
[14] J. W. Goodman, "Some fundamental properties of speckle," *J. Opt. Soc. Amer.*, vol. 66, no. 11, pp. 1145–1150, 1976.
[15] I. Yılmazlar and M. Sabuncu, "Speckle noise reduction based on induced mode hopping in a semiconductor laser diode by drive current modulation," *Opt. Laser Technol.*, vol. 73, pp. 19–22, Oct. 2015.
[16] J. W. Goodman, *Speckle Phenomena in Optics: Theory and Applications*. Englewood, CO, USA: Roberts, 2007.
[17] F. Riechert *et al.,* "Speckle characteristics of a broad-area vcsel in the incoherent emission regime," *Opt. Commun.*, vol. 281, no. 17, pp. 4424–4431, Sep. 2008.