Reconfigurable and Fault Tolerant Digital Phase Shifted Modulator for Luminance Control of LED Light Sources

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Abstract—This paper presents a digital phase shifted modulator (PSM) for luminance control of high brightness light emitting diode (HB-LED) based light sources. The design of the modulator is optimized to meet the growing demand for flexible, fault tolerant and hardware efficient dimming capability for LED lamps with a large number of series LED strings. Depending on the LED lamp specifications, the modulator can be configured to generate an arbitrary number of time synchronous as well as uniformly phase shifted output pulses. In case of LED string failure, two different online fault recovery techniques are introduced. After a fault event the modulator maintains the total LED lamp luminance by scaling the duty cycle of the control outputs, \( c_i \) or the forward current through the operating LED strings, \( I_{\text{ref}} \). The desired resolution (dimming ratio) is achieved by performing \( \Sigma \Delta \) modulation of the input command and using a single high resolution DPWM module. Experimental results are presented for a system with 8 strings of series LEDs and an input command of 10-bit resolution.

I. INTRODUCTION

The luminous flux generated by a high brightness light emitting diode (HBLED) is a function of the forward biased current flowing through the p-n junction and the die temperature [1-3]. At constant temperature, the luminous flux emitted from an HBLED is linearly dependent on the magnitude of the forward current flowing through the junction, enabling current controlled operation of the device. A number of techniques, based on either amplitude or pulse modulation of the current, have been proposed to control the light generated by a lamp consisting of tens to hundreds of LEDs [4-6]. Amongst them, pulse width modulation (PWM) of the LED forward biased current has emerged as a favorable method due to its ease of implementation as well as linear response characteristics over a wide range [8,7]. For a typical LED light source containing a parallel network of multiple series LED strings [9-11], conventional fixed frequency PWM dimming is achieved by simultaneously turning all LED strings ‘on’ and ‘off’ for complementary periods of time, determined by the input dimming command [12-14].

Conventional PWM dimming results in large input current transients and therefore requires a large source capacitance and EMI filter. In order to reduce the magnitude of input current transients generated and to improve the system efficiency, an alternative dimming approach based on uniform phase shifting of the pulsed LED current was proposed in [15]. Based on the dimming command, the magnitude of load current transients is now limited to a value less than or equal to a single LED string current. The LED power stage can then be operated with reduced output bus capacitance and better EMI performance. Modulator architectures, capable of achieving uniform phase shifting for a fixed number of predetermined outputs have been described in literature [16-18]. However the limited flexibility and inability of these architectures to respond to LED fault conditions limits their use as a PWM controller for LED lamps.

LED open circuit failures are generally caused by thermo-mechanical stresses generated within the LED package at elevated operating temperatures which result in rupturing of the LED bond wire or LED chip detachment from die-attach [19-22]. LED short circuit failure mechanisms are related to formation of threading dislocation defects across the active region and contact electromigration when operating under high current stress [23-26]. For flip-chip packaging technology, short circuit failures can occur due to formation of solder balls or whiskers at high temperature operation [22]. For a lamp configuration shown in Fig. 1, an LED open circuit failure results in loss of light output generated from an entire string while a LED short circuit failure results in increased...
losses and reduced efficiency of the system. To improve the LED lamp system reliability and extend the operating life, it is necessary to detect and mitigate the above fault conditions.

This paper presents an improved digital phase shifted modulator (PSM) that can be configured to generate an arbitrary number of uniformly phase shifted outputs and is capable of online recovery from individual LED string failures. The occurrence of individual LED string failures is communicated to the modulator using an external Fault detection block. For a regulated power supply voltage, \( V_s \), the changes in LED characteristics can be tracked by measuring the node voltage, \( V_n \), across each current sink regulator. Comparing the change in the node voltage \( V_n \), against a pre-calibrated reference, LED failure can be detected. Depending on the desired resolution, two or more comparators can be used to digitize the voltage, \( V_n \). The digital error value, calculated by subtracting the measured voltage from a programmed digital reference, can be used to generate a fault signal. On detection of a LED failure, the modulator functionality is adapted to maintain the uniform phase shift amongst the remaining operating strings along with the total luminance of the lamp. Two different operating modes and fault mitigation algorithms are introduced in the paper: one based on scaling the duty cycle while maintaining the LED forward current constant and the other based on increasing the LED forward current while maintaining the duty cycle constant.

The proposed reconfigurable and fault tolerant phase shifted modulator architecture is introduced in Section II. The operating principles, hardware implementation circuits and dimming command to light output transfer function characteristics for each of the modulator operating mode are presented in detail. Experimental results for a test system, consisting of 8 parallel strings of 8 series LEDs rated at 140 mA, are provided in Section III. Section IV concludes the paper.

II. RECONFIGURABLE AND FAULT TOLERANT PHASE SHIFTED MODULATOR

The block diagram of the proposed reconfigurable and fault tolerant phase shifted modulator is shown in Fig. 2. The modulator is subdivided into three distinct functional blocks, a Modulator core, a Signal processing block and a Current scaling block. Depending on the LED power ratings, the total number of LED strings operating, \( N_o \), and the number of current sink regulators present in the hardware, \( N_s \), the Modulator core is programmed to generate high resolution time synchronous as well as phase shifted control outputs, \( \{ c_i \} \). The Signal Processing block manipulates the input dimming command before feeding it to the Modulator core so as to achieve the desired luminance resolution (dimming ratio) during normal as well as fault conditions. The current reference signal that controls the amplitude of forward current through each LED string and hence the peak luminance of the LED lamp, is generated by the Current scaling block.

The modulator operating mode is programmed by the external enable/disable commands. Online event-driven reprogramming of the modulator occurs when a fault conditions is communicated by LED fault status bus, \( F \).

The hardware implementation details along with the working principles of the Modulator core are first described. The lamp characteristics when operating under duty cycle scaling mode and current scaling mode are presented. Operation of \( \Sigma-A \) modulation along with its effect on the perceived luminance and flicker is then explained in detail.

A. Modulator core

The Modulator core leverages the hardware efficient architecture presented in [15,16] to generate high resolution output pulses based on a \( p \)-bit input dimming command, \( D_{in} \), that controls the ‘on’ time of the linear current sink circuits. Based on the maximum number of current sinks available in hardware, \( N \), the command, DPWM, is split into an \( n \)-bit MSB (most significant bits) and \( m \)-bit LSB (least significant bits) command, where \( n \) and \( m \) are defined as

\[
n = \text{ceiling} \left( \frac{\log(N)}{\log(2)} \right) \quad \text{and} \quad m = p - n.
\]

The MSB command \( d_{MSB} \) is the input to the \( n \)-bit Binary-to-Thermometer Decoder. The thermometer code output, \( \{ t_1, t_2, t_3, \ldots, t_{N-1} \} \) controls the exact number of LED strings, \( k \), that are on at any given time based on the \( d_{MSB} \) input.
command,
\[
t_i = \begin{cases} 
1, & 1 \leq i \leq k \\
0, & k + 1 \leq i \leq N - 1
\end{cases}.
\]

The LSB command \(d_{LSB}\) is the input to the \(m\)-bit DPWM module that generates a high-resolution time resolved signal, \(I_{0}\). Hardware efficiency is achieved by time sharing the high resolution DPWM output amongst all modulator outputs.

The **Programmable Selector** block performs a time-dependent mapping from \(\{t_i\}\) to control outputs \(\{c_i\}\) using \(N\) multiplexers. Instead of using an \(n\)-bit binary counter and predetermined mapping logic, as in [16], the block uses a single programmable modulo \(N_{c}\) down counter and output mapping logic to achieve uniform phase-shift for an arbitrary number of outputs. The number of control outputs and the phase shift between them can be changed by setting the appropriate bits in the mapping register, \(M\), and by enabling or disabling the logic switches \(\{s_0, s_1, s_2 \ldots s_{N-1}\}\) in the output mapping logic. In the case when \(N\) number of LED strings are operating \((N_c = N)\), uniform phase shift amongst them is obtained by setting all bits in register, \(M\) to logic high and programming the counter to value \(N\). The output of the adjacent multiplexers is now shifted by one MSB clock period. As the counter progresses \((e.g\) counts in reverse \((N-1, N-2 \ldots 1, 0, N-1)\)\) phase rotation is achieved between the multiplexers resulting in uniformly phase shifted output pulses \(\{c_i\}\). The high resolution \(t_o\) component is naturally appended to the falling edge of the on/off control signal, \(\{c_i\}\) as designated by the phase rotation counter. Two or more time synchronous control outputs can be generated by setting the corresponding bit(s) in the mapping register to logic zero, thus allowing parallel connection of current sink regulators. A part of the modulator can now be programmed to operate as a conventional PWM while the other part can operate as a PSM, providing design flexibility.

During normal operation the **LED fault status bus**, \(F\), designates which LED strings are active and communicates the event of LED failure from the **Fault detection** block. When one or more operating string fails the phase shifting of the modulator property is lost and the magnitude of input current step transient increases. This may cause the LED module power supply to malfunction or fail. The online configuration of the modulator is performed to restore the lamp luminance and the uniform phase-shift between remaining operating LED strings, \(N_{o}\).

### B. Modulator operation with duty cycle scaling

Operation in this mode is configured by disabling the **Scaling logic** block, the **Current scaling** block and setting the current reference signal, \(I_{ref}\), to a fixed value. For the case when the **Modulator core** resolution is greater than or equal to the input dimming command \((p \geq q)\), the \(\Sigma\Delta\) **Noise shaping** block is also disabled \((D_N = D_{sat})\). During normal operation, the ‘on’ time of control output pulse, \(t_{on}\), is determined by the input dimming command and the input clock frequency, \(f_{clk}\) and is independent of the number of LED strings operating;
\[
t_{on} = \frac{D_{dim}}{f_{clk}}.
\]

On an LED string failure, the phase shift for the control output, designated by **LED status bus**, \(F\), is disabled by setting the corresponding bit in mapping register, \(M\), to logic low. The current sink regulator operation for the failed LED string is disabled by setting the logic switch, \(\{s_i\}\), to logic low or high impedance state. In order to maintain a uniform phase-shift between the remaining number of operating strings, \(N_{o}\), the count value is decreased to a corresponding value \(N_{c}\). For a constant clock input frequency, \(f_{clk}\), the operating frequency of the active control outputs, \(f_c\), increases and is given by
\[
f_c = \frac{f_{sat}}{N_{o}} \cdot 2^m
\]

The control output duty cycle of operating LED strings, \(d_c\), naturally scales in proportion with the operating frequency and hence the number of operating LED strings. The light output from the lamp and the desired resolution of the modulator is maintained for a range of dimming command values with no additional hardware requirements. The duty cycle and the luminance of the lamp \((L)\) saturates when the pulse ‘on’ time, \(t_{on}\), equals or exceeds the total time period \((1/f_{clk})\), corresponding to dimming command range, \(D_{dim} \geq D_{sat}\), where
\[
D_{sat} = N_{o} \cdot 2^m
\]

The characteristics of the modulator with 10-bit input dimming command and up to 8 operating LED strings are shown in Fig. 3, where \(L\) is the lamp luminance and \(L_{\text{max}}\) is the peak luminance measured when all 8 strings are operating at 100 % duty cycle. The minimum hardware requirements of this approach make it suitable as a cost effective implementation of the modulator to control LED lamps that operate at intermediate luminance values. By de-rating lamp design, total luminance specification can
directly resolve the scaled dimming command

be maintained even after losing one or more LED strings and hence the system reliability and life span can be improved.

C. Modulator operation with current scaling

In this operating mode, the Scaling logic and Current scaling blocks are enabled. Linear response across the entire dimming range is maintained by scaling down the dimming command, \( D_{\text{dim}} \), based on the number of LED strings, \( N \). The Scaling logic block, scales the \( q \)-bit dimming command by a fractional \( n \)-bit scale factor, \( S_F \), to generate a \((q+n)\)-bit output, \( D_r \). The scaling factor and output command \( D_r \) are computed as

\[
S_F = \frac{N}{2^n} \quad \text{and} \quad D_r = D_{\text{dim}} \cdot S_F. \tag{7}
\]

When the DPWM resolution is greater than or equal to the dimming command input \((m \geq q)\), the Modulator core can directly resolve the scaled dimming command \( D_r \) to generate the desired resolution control outputs, \((p = q+n)\).

The scaled dimming command is then directly fed to Modulator core, \((D_M = D_r)\).

When the Modulator core hardware is designed to resolve a \( q \)-bit input dimming command \((p = q+n)\), feeding a \((q+n)\)-bit scaled dimming command, \( D_r \), directly to the modulator results in decreased control output resolution. In this case, the \( \Sigma-\Delta \) Noise shaping block can be enabled to interface between the Scaling logic block and Modulator core to maintain the desired resolution. The Modulator core processes the input command, \( D_M \), to generate uniformly phase shifted control outputs during normal as well as fault operations, in a manner similar to that described in sections II-A and II-B.

For a constant LED forward biased current, the peak light output generated from the lamp decreases with the decreasing number of operating LED strings. In order to maintain the peak luminance, the forward current through the operating LED strings is scaled by the Current scaling block and is made inversely proportion to the scale factor, \( S_F \).

\[
I_{\text{ref}} = \frac{I_{\text{ref}, N}}{S_F}, \tag{8}
\]

where \( I_{\text{ref}, N} \) is the reference current set for the condition when all \( N \) number of LED strings are operation. Based on the LED current ratings and the total power dissipation limits of the linear regulator, an \( N \)-entry look-up table is programmed during manufacturing to store the reference values corresponding to different number of LED strings operating. On occurrence of an LED string failure, the scale factor, \( S_F \), is used to select the corresponding entry from the look-up table to generate the \( z \)-bit digital current reference command, \( I_{\text{ref}} \).

The characteristics of the modulator with up to 8 operating LED strings are shown in Fig. 4, where \( I_{\text{ref}, 8} \) is the reference current when all 8 strings are operating. The desired resolution duty cycle is maintained by performing \( \Sigma-\Delta \) modulation and a linear response between lamp luminance and 10-bit input dimming command is maintained by scaling the reference current, \( I_{\text{ref}} \), flowing through the LED.

The current scaling mode of operation is suitable for LED lamps installed in applications that require precise control of the lamp luminance. Reliable performance and extended lamp life can be achieved by designing the lamp such that the maximum scaled LED current under fault conditions does not exceed the absolute maximum device ratings.

D. \( \Sigma-\Delta \) modulation to improve system resolution

For the case when the hardware resolution of the Modulator core is insufficient to resolve the input command, operation of \( \Sigma-\Delta \) modulator is enabled to maintain the desired resolution. The command \( D_{\text{dim}} \) or \( D_r \) is truncated by \( r \)-bit LSB to generate the \( p \)-bit command, \( D_M \), output fed to the Modulator core. This introduces a truncation error, \( e \), given by \( 2^{-r} \leq e < 0 \), into the system which results in reduced resolution. By employing noise shaping techniques, the truncation error can be reduced or eliminated and the desired system resolutions can be achieved [27-29].

The design of a \( \Sigma-\Delta \) modulator for a LED source is based on the understanding that the human eye-brain system is almost an ideal low-pass filter and has a finite persistence. The low-pass filter cut-off frequency, referred to as critical flicker frequency, \( f_{fc} \), is a function of the eye adaptation to ambient light conditions and for a light source is widely accepted to be equal to 60 Hz \((f_{fc} = 60 \text{ Hz})\). According to Talbot-Plateau law, if a light source is flashed or pulse at a rate above the critical flicker frequency, the perceived luminance of the modulated source \([30]\), \( L(t) \), will be equal to that of steady light source which has the same time-average luminance, \( L_M \) i.e.

\[
L_M = \frac{1}{T} \int_0^T L(t) \, dt. \tag{9}
\]

The \( \Sigma-\Delta \) modulator ensures that the time average of the output signal, \( D_M \), equals that of the input signal \( D_{\text{dim}} \) or \( D_r \). However, the gain in resolution that can be achieved by using noise shaping techniques is limited due to subharmonic idle tones (limit cycles) generated by a constant or a slowly varying input signal \([28]\). The tone frequencies in PSM depend on various system parameters like the output control signal frequency, \( f_c \), the number of...
LED strings operating, the order of the $\Sigma\Delta$ noise transfer function (NTF) and the hardware resolution. When the tones are present at a frequency below critical flicker frequency ($f_c = 60$ Hz for ambient light conditions), lamp flicker is visible. In order to avoid flicker perception, it is necessary to clock the modulator at a frequency high enough so that the tones appear at frequencies above critical flicker frequency. For an error signal of $r$-bit and first order NTF, the minimum output control signal pulse frequency, $f_r$, required to avoid flickering is calculated as,

$$f_r = 2 \cdot 60 \text{ Hz} \cdot \left( \frac{r}{10} \right)$$

As the output frequency always increases on the occurrence of LED string failure, the tones always move towards higher frequency, further eliminating the possibility of flicker sensation during fault conditions.

III. EXPERIMENTAL RESULTS

The complete experimental setup is shown in Fig. 5, in which the proposed phase shifted modulator, implemented on a Virtex-4 FPGA board, controls the current through 8 LED strings, ($N = 8$). Each LED string contains 8 series connected white LEDs with rated operating current of 140 mA and is powered from a 35 V regulated power supply bus ($V_g = 35$V). The current through each LED string is regulated by an op-amp based linear current sink circuit. The amplitude of the current is set by the reference command, $V_{ref}$, generated from an 8-bit DAC and 10 $\Omega$ resistor, $R_s$ and can be varied from 0 to 328 mA. The duration of the pulses at the modulator outputs, $\{c_i\}$ is controlled by toggling the analog switch positions, $\{s_i\}$. An 8:1 analog multiplexer samples the voltage across the current sink regulator, $V_{\text{in}}(t)$, the output of which is then compared to an upper and lower limit of 12 V and 3 V respectively. During normal operation, the voltage across each LED string varies between 25 V to 30 V, for which the comparison results in a logic high signal. In case of a catastrophic failure, the output of the comparator toggles state indicating a fault condition. The status of each LED string is communicated to the phase shifted modulator through a 2-bit bus, $F$.

The dimming command and configuration inputs to the modulator are generated using a Xilinx Chipscope Pro Analyzer virtual input output core (VIO). An input dimming command of 10-bits is resolved by the phase shifted modulator to generate control outputs. The functionality of the modulator is configured by programming the 8-bit mapping register, $M$ and the 8 logic switches, $\{s_i\}$. The 3-bit mode select command is used to enable/disable the Scaling logic, Current scaling and $\Sigma\Delta$ Noise shaping blocks. The FPGA was programmed with the following key blocks: a 10-bit phase shifted modulator, consisting of a 13-bit Scaling logic, 1$^{st}$ order $\Sigma\Delta$ modulator, an 8-bit Current scaling block, a 3-bit Binary-to-Thermometer Decoder, a 7-bit DPWM module and eight 8-bit multiplexers.

In Fig. 6, modulator operation for 4 different LED lamp configurations is shown. For the case when 8 LED strings are operating, the modulator generates 8 uniform phase shifted control outputs as shown in Fig. 6 (a). Figures 6 (b), (c) and (d) illustrate the modulator operation for an LED lamp system with 5 LED strings operating, each with different power ratings. The time synchronous outputs generated by the modulator are used to parallel two or more current regulator circuits to drive a higher current through a high power LED string. Thus, by configuring the modulator, the same hardware architecture can be reused to design lamps with LEDs of different power ratings in order to meet the design specifications.

The duty cycle scaling and current scaling modes of operation are verified by simulating different fault conditions. The modulator is first configured in duty cycle scaling mode. With all 8 LED strings operating, the reference voltage is set to generate an LED forward current of 140 mA ($V_{\text{ref}} = 1.4$ V), and the modulator output frequency is set to 1 kHz ($f_c = 1$ kHz). A 10-bit input dimming command of $D_{\text{dim}} = 409/1024$, corresponding to 40 % duty cycle, is directly fed to the 10-bit Modulator core. Figure 7 illustrates the operation of modulator under fault conditions, when 7, 5 or 3 strings out of 8 are operating. On occurrence of a fault condition, the output frequency as well as the duty cycle value increases, until the point is reached where the duty cycle saturates to 100 %. For duty cycle less than 100 %, the total supply current, $I_s$, and hence the total light output generated by the LED array is maintained constant under fault conditions. The operation of the modulator is as predicted by the characteristics shown in Fig. 3.

In current scaling mode, the LED strings are configured to operate at a forward current of 75 mA and at frequency of 1 kHz ($f_c = 1$ kHz). The Current scaling block is programmed to scale the current from a nominal value of 75 mA to 200 mA ($V_{\text{ref}} = 2$ V). In order to limit the power dissipation in the current regulator circuit, the forward current through the LEDs is saturated at 200 mA. As the 10-bit Modulator core resolution is lower than the scaled dimming command, ($D_s = 13$-bit), $\Sigma\Delta$ modulator is enabled to maintain the desired resolution. The operation of the modulator in current scaling mode,
under simulated fault conditions, is shown in Fig. 8. On the occurrence of the fault, the duty cycle is maintained constant ($d_c = 40\%$) and the current through the individual LED is scaled from 75 mA to 200 mA. The average input current and hence the light output generated by the lamp is maintained during fault conditions. The linear characteristics from input dimming command to the light generated is maintained, as shown in Fig. 4.

For an operating frequency of 1 kHz, the lowest idle tone generated by the 1st order $\Sigma$-$\Delta$ modulator occurs at a frequency of 125 Hz, well above the critical flicker frequency limit. Based on the actual dimming command, the frequency as well as the magnitude of the tones generated will vary. The FFT magnitude spectrum of a single LED string current, with 7 LED strings operating, input dimming command of $D_{\text{dim}} = 409/1024$ and control output frequency of $f_c = 1143$ kHz, is shown in Fig. 9. Significant tones generated by the modulator are observed under simulated fault conditions, is shown in Fig. 8. On the occurrence of the fault, the duty cycle is maintained constant ($d_c = 40\%$) and the current through the individual LED is scaled from 75 mA to 200 mA. The average input current and hence the light output generated by the lamp is maintained during fault conditions. The linear characteristics from input dimming command to the light generated is maintained, as shown in Fig. 4.

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at 280 Hz and its multiples, again well above critical frequency. Tones generated at frequencies below 280 Hz have a magnitude below the noise floor and are small enough to not generate flicker sensation.

IV. CONCLUSION

A flexible and fault tolerant digital phase shifted modulator is presented that can generate time synchronous as well as uniformly phase shifted output pulses for an arbitrary number of LED strings. Two different operating modes, based on duty cycle scaling and current scaling of the LED forward current, are introduced to maintain lamp luminance under fault conditions. A uniform phase-shift between active LED strings is achieved by varying the output frequency. High resolution and good hardware efficiency is achieved by time sharing a single DPWM module amongst all active LED string outputs. The input dimming command resolution is maintained during fault conditions by performing $\Sigma$-$\Delta$ modulation. The operation of the proposed architecture for a system with 8 strings of series LEDs and a 10-bit input command is experimental verified.

REFERENCES