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An Eight-Channel Switching-Linear Hybrid Dynamic Regulator with Dual-Supply LDOs for Thermo-Optical Tuning

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Abstract—A novel switching-linear hybrid dynamic regulator with dual-supply LDOs for thermo-optical tuning is presented in this brief. Compared with conventional designs, the proposed design leverages the intrinsic dual supplies to extend the operating range of the LDOs, and increases the thermo-optical tuning efficiency by reducing the dropout of the LDOs through dynamic voltage tracking. It can simultaneously regulate eight output channels and track $0.8 V_{pp}$ sinusoidal waveforms at different frequencies. Significant efficiency improvement of the proposed design is achieved for envelope signals with a small difference, which is common in thermo-optical tuning. Implemented in 130 nm CMOS process, the proposed design has a total chip area of 0.675 mm^2 . The proposed design achieves a conversion efficiency of 88% at 1 V output driving a 200Ω load. Its dynamic efficiency is about 80% when tracking 50 kHz sinusoidal signals.

Index Terms—Thermo-optical tuning, hybrid dynamic regulator, dual-supply LDO, multiple output channels, envelope tracking.

I. INTRODUCTION

Thermo-optic tuning is the core dynamic control technology for photonic devices, and has been widely used in micro-ring resonator (MRR) [1], Mach-Zehnder interferometer (MZI) [2], silicon quantum photonic circuits [3], optical neural network (ONN) [4], and optical phased array (OPA) [5], etc. The thermo-optic tuning dynamically adjusts the effective refractive index of photonic devices by changing the device temperature and its general model is shown in Fig. 1. An on-chip resistor with a few hundred ohms is usually used as the heater [6]. By changing the power supply voltage of the resistor, the device temperature is easily adjusted. Most recent designs on thermo-optic tuning [1]–[4] apply PCB or benchtop power supplies, which are not practical for large-scale integrated systems. Few designs [5], [7] achieve the integration of the power supply, but the area of the power management circuit (PMC) is relatively large. Furthermore, there is still a lot of room for improving the system efficiency as well. For large-scale and energy-efficient thermo-optic tuning, a high-performance PMC with small chip area is required.

In traditional thermo-optical tuning, a linear power supply with fixed input voltage is widely used. However, this approach has a low tuning efficiency and causes additional

Fig. 1. A general model for the thermo-optical tuning in SiPh [6].

Fig. 2. Thermo-optic tuning of an MRR with (a) fixed power supply and (b) dynamic power supply; Voltage waveforms under (c) fixed power supply and (d) dynamic power supply.

TABLE I
COMPARISON BETWEEN TWO TYPES OF DYNAMIC POWER SUPPLIES

	Output Power	Envelope Tracking	Number of Channels
RF/AF PA	~W	$\geq 10\text{MHz (RF)}$ & 20kHz (AF)	Single
Thermo-Optic Tuning	~mW	$\leq 100\text{kHz}$	Multiple

heat dissipation problem. As shown in Fig. 2, we use an MRR to illustrate this problem. When the external environment temperature is unstable, the thermal regulator in Fig. 2 (a)(b) changes the output power by dynamically adjusting the V_{TH} to maintain the MRR's temperature, and stabilize the wavelength of MRR. For linear power supplies, the efficiency is inversely proportional to the dropout. When the V_{TH} decreases, the

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power efficiency with fixed inputs will significantly drop. Alternatively, using a dynamic power supply in Fig. 2 (b) can reduce the dropout voltage, therefore improving the power conversion efficiency of the power supply.

Dynamic power supplies have traditionally been used in radio-frequency power amplifiers [8]–[11] and audio-frequency power amplifiers [12]. However, the dynamic power supply for thermo-optic tuning is quite different from the above applications in terms of power range, envelope tracking (ET) speed, and the number of channels. For general thermo-optic tuning, the required output power is only about tens of mW [6], and the typical bandwidth is around tens of kHz [6]. Meanwhile, multi-channel thermo-optic tuning is used in many applications, which requires multi-channel dynamic regulators. TABLE I compares the differences between these two types of dynamic power supplies. Furthermore, most existing schemes are board-level designs, and cannot meet the large-scale electronic-photonics integration requirements.

In this brief, we present a novel eight-channel switching-linear hybrid dynamic regulator with dual-supply LDOs supporting both high conversion efficiency and wide tuning range. The remainder of this brief is organized as follows. Section II presents the structure and operating principles. Section III shows the simulation results. Section IV draws the conclusion.

II. EIGHT-CHANNEL HYBRID DYNAMIC REGULATOR

The architecture of the proposed eight-channel switching-linear hybrid dynamic regulator with dual-supply LDOs is shown in Fig. 3. The architecture has intrinsic dual supplies, i.e., the global supply V_{DD} and the intermediate supply V_A . It is mainly composed of an envelope processor, a buck converter with fully-integrated current-mode Type-III compensator, lightweight local generated supplies (LLGS), and eight parallel dual-supply LDOs with NMOS power stage. V_{Env} is the envelope of all input signals, which is generated by the envelope processor. The envelope processor assists the buck converter to generate a suitable first-stage output voltage V_A , which should be as low as possible but ensure the normal operations of the second power stage. The LLGS and the switching converter share the global supply voltage V_{DD} . The function of the LLGS is to provide an appropriate local voltage for the controllers of the dual-supply LDOs. Meanwhile, the power stages of the LDOs are connected to the output of the switching converter and supplied by V_A . This design can alleviate the restriction on the minimum V_A by the controller of the second-stage LDO without adding additional complexity. In addition, according to the changes of the input control signals V_{Env1} to V_{Env8} , the architecture can dynamically adjust the output V_A of the first-stage switching converter, thereby reducing the dropout of the second-stage converter. This will improve conversion efficiency and reduce the thermal crosstalk.

A. Envelope Processing Module

The envelope processing module is used to generate a suitable V_A for the second stage. Fig. 4 shows the structure of the envelope processing module. It consists of a maximum voltage

Fig. 3. Architecture of the proposed hybrid dynamic regulator.

Fig. 4. Structure of the envelope processing module.

Fig. 5. Schematic of (a) a simple dual-input maximum voltage selector and (b) the first-order butterworth active LPF.

selection module, a low-pass filter (LPF), and a non-inverting adder. Fig. 5 shows a simple dual-input maximum selector and the LPF used in this brief. Cascading multiple dual-input maximum voltage selectors can achieve the maximum selection of multiple signals. The first-order butterworth active LPF with 500 kHz cut-off frequency is designed to filter out the high-frequency components of the envelope signal which are outside the bandwidth of the buck converter. V_{Env_AC} is the envelope signal of all input signals. With the non-inverting adder, V_{Env} equals to the superposition of the V_{Env_AC} and a DC offset. As $V_A = 2V_{Env}$ while $V_{THi} = 2V_{Env_i}$ ($i = 1, 2, \dots, 8$), the dropout between V_A and the max $\{V_{TH1}, V_{TH2}, \dots, V_{TH8}\}$ equals to $2V_{Offset}$. By adjusting the value of V_{Offset} , the minimum dropout can be guaranteed in most operating situations, thereby improving the conversion efficiency and minimizing the thermal crosstalk. In this brief, the DC offset is around 20 mV.

Fig. 6. Structure of the current-mode dual-path Type-III compensated buck converter.

Fig. 7. Schematic of the dual-supply LDO.

Fig. 8. Schematic of the lightweight local generated supply.

B. Buck Converter

Compared with the LDO, the switching converter has a high conversion efficiency. However, due to its relatively large chip area and output power, as well as its large off-chip inductors and capacitors, it is not suitable for directly supplying the resistive heaters in large-scale thermo-optic tuning. In this

design, the switching converter is used to supply multiple power stages of the LDOs. As the dropout between V_A and the $\max \{V_{TH1}, V_{TH2}, \dots, V_{THn}\}$ can be compressed to within tens of mV, the overall efficiency of the system will be greatly improved.

The buck converter in this design is based on [13], it has been demonstrated in [13] that the buck converter with monolithic current-mode dual-path Type-III compensator has an excellent transient response and a high f_{ugb}/f_{sw} ratio compared with most recent works in the literature. It can track 180kHz SC-FDMA waveforms, which is adequate for our application. Fig. 6 shows the structure of this current-mode dual-path Type-III compensated buck converter.

C. Dual-Supply LDO with LLGS

The LDO for thermo-optic tuning has different requirements compared with the design for other applications. To support the high-speed and wide-range thermo-optic tuning, the LDO with wide bandwidth and large output range is required. As the load of the LDO for thermo-optic tuning can be regarded as a fixed purely resistive load, there is no need to consider the transient response caused by the load changes. The dropout of the LDO is the main factor affecting the efficiency of the LDO. By separately supplying the controller and the power stage of the LDO, the dual-supply configuration expands the operating range of V_A , which allows us to reduce the minimum dropout of the LDOs. By reducing the dropout, the system efficiency is thus significantly improved.

Fig. 7 shows the schematic of the dual-supply LDO. The control stage of the LDO is a two-stage amplifier with current-mirror miller (CMM) compensation proposed in [14]. To suppress the interference of the V_A 's changes and the ripples on the output of each channel, we select NMOS as the LDO's power stage. The simulation result shows that the PSR of the LDO has a 25 dB improvement compared to using PMOS as the power stage in this design.

Fig. 9. Key waveforms of V_A , V_{TH1} , and V_{TH2} when the voltage difference between different channels is (a) large or (b) small.

Fig. 10. Layout of the proposed design.

Fig. 11. Compare (a) the dropout and (b) the efficiency between the proposed design and the conventional design.

Fig. 12. Key waveforms of (a) V_{Env1} to V_{Env8} ; (b) V_{Env} and V_A ; (c) V_{TH1} to V_{TH8} , respectively in the steady state.

The LDO with NMOS power stage conventionally has a relatively large dropout and a narrow dynamic range, which is undesirable for thermo-optic tuning. To solve this problem, we introduce the lightweight local generated supply (LLGS) structure in [15] to supply the control stage. The LLGS provides a sufficiently high local voltage V_{LLGS} for the controller to have enough gain and a wide dynamic range. As shown in Fig. 8, the LLGS includes an error amplifier, a relatively small power transistor, and a two-stage charge pump. For the LLGS, the output voltage V_{LLGS} is mainly determined by V_{SET} and has nothing to do with V_{DD} .

D. Evaluation of Efficiency

As the power consumption of the envelope processing module is negligible, the overall conversion efficiency of the system for channel i ($i = 1, 2, \dots, 8$) can be written as

$$\eta_i = \eta_{con} \cdot \eta_{ldo_i} \quad (1)$$

$$\eta_{ldo_i} \simeq \frac{I_{load} V_{THi}}{I_{load} V_A + I_q V_{DD}} \quad (2)$$

where η_{con} and η_{ldo_i} are the efficiency of the switching converter, and the channel i of the dual-supply LDOs, respectively; I_{load} and V_{THi} are the load current and the output voltage of the same channel; I_q is the quiescent current of the LDO and LLGS.

The efficiency of the multi-channel dynamic regulator is related to the dynamic changes of the multi-channel envelope as well. Since the multiple channels share the same intermediate voltage V_A , it is impossible for the architecture to individually adjust the dropout of each linear power stage. As shown in Fig. 9, the dynamics of the envelope can be divided into two typical situations. The improvement of the system efficiency is relatively limited for V_{TH2} when the voltage difference between V_{TH1} and V_{TH2} is comparatively large in Fig. 9 (a). Fortunately, in thermo-optic tuning, it is common that the voltage difference between each channel is small, which has been shown in Fig. 9 (b). The proposed architecture exactly has an obvious efficiency improvement for this case.

III. POST-LAYOUT SIMULATION RESULTS

The proposed hybrid dynamic regulator structure has been implemented in 130 nm CMOS technology, and Fig. 10 shows the layout of the proposed design with a total area of 0.675 mm². Fig. 11 verifies that the proposed design not only extends the operating range of the LDOs, but also greatly improves the efficiency under the same dropout between V_{DD} and V_{TH} . The efficiency is simulated when the load current of each channel is 5 mA. The conventional design cannot work when the dropout is less than 0.37 V while the proposed design can still keep the efficiency of around 88%. Fig. 12 shows the key waveforms in the steady state when V_{Env1} to V_{Env4} , and V_{Env5} to V_{Env8} are 50 kHz 0.4 V_{pp} , 40 kHz 0.3 V_{pp} , 30 kHz 0.2 V_{pp} , and 20 kHz 0.1 V_{pp} sinusoidal waveforms respectively.

The static efficiency of the proposed design when each channel loads the same current is shown in Fig. 13. The peak

TABLE II
COMPARISON AND SUMMARY

	[8] JSSC 2012	[9] ISSCC 2007	[10] JSSC 2017	[11] JSSC 2008	This Work
Application	10MHz LTE	EDGE Polar Transmitters	PA	CDMA Transmitters	Thermo-Optical Tuning
Tech.(nm)	150	350	130	350	130
Channels	1	1	1	1	8
Supply Voltage(V)	4.5	3.5	1.2	3.3	1.2
Output Voltage(V)	N.A.	0.4-3	0.2-1	0.3-3	0.25-1.05
Peak Efficiency	82%	88.3%	88.2%	82%	94.7%
Dynamic Efficiency	79% @ 1MHz LTE Signal	N.A.	81% @ 13MHz Sine	N.A.	80% @ 50kHz Sine
E/T	200kHz (Square)	50kHz (Square)	13MHz (sinusoidal)	CDMA Envelope signal	50kHz (sinusoidal)
Load Resistor(Ω)	8	4	5	4.4	200
Chip Area(mm ²)	1.6	4.7	0.15	4.62	0.675

Fig. 13. The static efficiency of the proposed design.

Fig. 14. The dynamic efficiency of the proposed design.

power conversion efficiency is 94.66% when the output voltage is 1 V, and the load current of each channel is around 40 mA. When driving a 200 Ω load, the proposed design achieves the conversion efficiency of 88.6% at 1 V output. The dynamic efficiency of the proposed design when each channel tracks the same sinusoidal waveforms is shown in Fig. 14. The proposed design achieves a dynamic efficiency of around 80% tracking 50 kHz sinusoidal waveforms and driving a 200 Ω load, while the ideal efficiency of the conventional design under the same situation is at most 61.1%. The dropout between V_A and V_{TH}

is both 40 mV when testing the static and dynamic efficiency. The performance of this design is summarized and compared in TABLE II.

IV. CONCLUSION

In this brief, we have proposed a novel eight-channel switching-linear hybrid dynamic regulator with dual-supply LDOs, whose architecture has great potential for large-scale thermo-optical tuning. Compared with the fixed power supply, this design reduces the dropout and significantly improves the conversion efficiency, especially for the envelope signals with a small difference. Higher system efficiency is expected by further improving the efficiency of the switching converter. A prototype with post-layout simulation results has been used to verify the advantages of the proposed architecture. Nevertheless, the operating principle is general and can be implemented with other switching converters and LDOs.

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