A DLL based clock multiplier using rotational DCDL and PRNG for spur reduction

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Abstract: This paper presents a DLL based clock multiplier with a novel spur reduction technique. By randomly selecting delay line with pseudo random number generator (PRNG), the proposed scheme reduces the output spur due to delay cell mismatches. Rotational digitally controlled delay line (DCDL) is also proposed for seamless generation of clock edges even at random delay line switching. The clock multiplier is designed in 0.18 μm CMOS process and achieves 5~11 dB reduction of spur while consuming 169.4 μW for 16 MHz. The core area is 0.608 mm^2 .

Keywords: DLL, digital DLL, clock multiplier, spur reduction, PRNG

Classification: Integrated circuits

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1 Introduction

The clock multiplier is an important building block in clock/frequency generation in wireless communication systems and System-on-chip (SoC) [1, 2]. A phase locked loop (PLL) is widely used architecture for clock multiplication. However, PLL is basically two pole system, one from the loop filter and the other from the oscillator, and so there is a tradeoff between bandwidth and stability. Due to the limited choice of loop bandwidth, the PLL has an inevitable issue of jitter accumulation [3]. On the other hand, the delay locked loop (DLL) is a single pole system since the loop filter voltage instantly change the output delay. Compare to PLL, therefore, the DLL typically has less jitter accumulation and less settling time. [4, 5].

The DLL-based clock multiplication uses an edge-combining technique [6] from multiple clock edges at the delay chain. Therefore, any mismatches in delay cell due to process variation and inadequate layout design cause spurious tone at output [7, 8]. Assuming the delay of one delay cell is longer than that of the others, this delay difference appears in the output waveform with a period of the reference clock. In frequency domain, the spur will appear at the offset frequency corresponding to the harmonics of the reference frequency around the output frequency. Static phase offset due to current mismatch of charge pump in analog DLL also contributes to the spur level.

Several researches have reported spur reduction techniques for DLL-based clock multiplier [7, 8, 9]. In [9], a current-splitting charge-pump is adopted to reduce the reference spur by the static phase offset, resulting reference spur level below -39.2 , -36.8 , and -26.2 dBc for $\times 2$, $\times 3$, $\times 6$ clock multiplication, respectively. In this paper, we introduce delay line scrambling technique to reduce the spur levels due to delay cell mismatches. This paper is organized as follows. In section 2, we describe the proposed DLL-based clock multiplier and circuit implementations. The section 3 and 4 present implementation results and conclusion, respectively.

2 Proposed architecture

The block diagram of the proposed clock multiplier is shown in Fig. 1. Reference clock (f_{ref}) is injected to rotational digitally controlled delay line (DCDL) for multiple clock edge generation. Pseudo random number generator (PRNG) based DCDL decoder randomly selects delay line in rotational DCDL to shape delay cell mismatches. Matrix switch performs reordering of output phases for edge combiner which finally generates multiplier clock, f_{out} . For $\times 16$ clock multiplication, 16 output phases ($\Phi_{o1\sim 16}$) are applied to edge combiner. Phase output Φ_{o17} exhibits the same phase of Φ_{o1} , and is used for phase detector (PD). PD [10] generates 1b up/down signal for digital loop filter (DLF) operation. This digital DLL implementation eliminates the charge pump and minimizes the spur from the static phase offset.

Fig. 1. Top block diagram of proposed DLL-based clock multiplier

2.1 Rotational DCDL and matrix switch

The proposed rotational DCDL consists of a ring-shaped rotational delay line composed of 18 delay cells, 18 branch delay lines composed of 4 delay cells, and control switches, as shown in Fig. 2(a). Each delay cell is controlled by the control voltage from 12b digital to analog converter (DAC), described in the section 2.3. Switch control signal (Sel_{DCDL}) from DCDL decoder decides f_{ref} injection points and one of the 18 branch delay line. For example, if f_{ref} is applied to the input of the 3rd delay cell (d_3), the 15th branch delay line ($d_{15_1\sim 4}$) is selected for total 17 output clock edge generation (Fig. 2(b)). If DCDL decoder selects the 10th delay cell (d_{10}) for f_{ref} injection point, the 4th branch delay line ($d_{4_1\sim 4}$) is used for output phase generation. Therefore, total 18 delay line configurations are possible with designed rotational DCDL. Note that unselected branch lines are turned off to save power consumption.

Random selection of one of 18 delay lines scrambles mismatches in delay cells, and consequently reduces the spur level at output. If 12th delay cell (d_{12}) has a

larger delay than other delay cells and f_{ref} is always applied to the input of the 3rd delay cell (d_3) as in case of Fig. 2(b), 10th clock edge of output clock always shows more delay than others. Since such delay change is repeated in every f_{ref} period (T_{ref}), it is the source of spurs at the harmonic offsets of f_{ref} in output spectrum. However, if f_{ref} is injected to d_{10} in next cycle, in case of Fig. 2(c), 3rd clock edge of output clock shows more delay than others and the periodicity of delay change is no longer T_{ref} . In other words, although delay cell mismatches still exist in the delay line, the periodicity of delay change is scrambled with the proposed randomized delay line selection and the spur power at the harmonic offsets of f_{ref} are also spread out.

All the outputs of delay cells in DCDL are connected to matrix switch since the points at which the clock edges are output are different for each delay line selection. With a control from matrix decoder, matrix switch rearranges and outputs 17 phases for each selection. For example, in case of Fig. 2(b), output of d_3 and $d_{15,4}$ are used for Φ_{o1} and Φ_{o17} , respectively, while output of d_{10} and $d_{4,4}$ are used for Φ_{o1} and Φ_{o17} , respectively, in case of Fig. 2(c).

Fig. 2. (a) Proposed rotational DCDL architecture (b) when f_{ref} is applied to d_3 (c) when f_{ref} is applied to d_{10}

Fig. 3 shows the timing diagram of rotational DCDL where f_{ref} injection point is changed from d_3 to d_{10} . After f_{ref} is applied to d_3 , 13 clock edges are output from delay cell outputs ($d_{30\sim150}$) in order. The next 4 clock edges are then output ($d_{15,10\sim15,40}$) from the branch delay line connected to the d_{15} output. The rotational delay cells ($d_{1\sim18}$) are reset (RST_{DCDL}) in synchronization with the first branch

delay cell output (in this case, $d_{15_{10}}$), and Sel_{DCDL} also moves to next injection point (in this case, d_{10}). Since rotational delay line is reset to low value before f_{ref} arrives, switching to any delay line configuration is possible regardless of f_{ref} duty cycle. At the same time, since the remaining clock phases are output in the selected branch line, which are not reset, total 17 phases for clock multiplication and phase detection are continuously generated.

Fig. 3. Timing diagram of rotational DCDL where f_{ref} injection point is changed from d_3 to d_{10}

2.2 PRNG

The PRNG consists of 8b linear feedback shift register (LFSR) for sufficiently long pseudo random codes, and delta sigma modulator (DSM) for output bit conditioning and further randomization (Fig. 4). The PRNG output (OUT_{PRNG}) has a digital output of 5b for total 18 delay lines selection. To provide only 18 selection code out of 32 possible binary 5b representation, 18 level quantization (right side table in Fig. 4) is adopted at DSM quantizer.

Fig. 4. Circuit diagram of PRNG

2.3 DLF and DAC

Fig. 5(a) shows the DLF that consists of 12b integrator, a binary-to-thermometer code converter (B2T) and DSM. After integrating 1b PD output with 1 MHz ($= f_{ref}$) clock, the 4 most significant bits (MSBs) of 12b integrator output are directly applied to DAC for coarse tuning. Next 4 bits are converted to thermometer code to improve overall linearity of DAC, and used for fine tuning. The 4 least significant bits (LSBs) are converted to 1b stream with DSM with 16 MHz clock ($= f_{out}$) to further improve DAC resolution. Circuit diagram of DAC is shown in Fig. 5(b).

Fig. 5. The circuit diagram of (a) DLF, and (b) DAC in rotational DCDL

3 Post layout results

The proposed clock multiplier was designed in a 0.18 μm standard CMOS process and post layout verification was performed after RC parasitic extraction. Output frequency is 16 MHz with 1 MHz reference clock for low power sensor SoC application. Fig. 6 shows a chip layout which has a core area of $950 \mu\text{m} \times 640 \mu\text{m}$ ($= 0.6 \text{ mm}^2$). The total power consumption is $169.4 \mu\text{W}$.

Fig. 7 shows the output spectrum of the proposed clock multiplier. For performance comparison, intentional 1.5% mismatches are applied to delay cells, which generates -31.8 dBc worst case spur. In order to verify the validity of the proposed scheme more accurately, DCDL noise component obtained from phase

noise simulation result (-83.5 dBc/Hz @ 1 MHz, Fig. 8) is also included. The result shows that spur levels due to the delay cell mismatch are improved by 5~11 dB and now close to the spur levels without mismatch that is limited by the coupling effect from device parasitic capacitance in multiplexer switches for f_{ref} injection. The worst case spur level is improved from 31.8 dBc to 38 dBc. The RMS and peak-to-peak jitter are 1.1 ns and 21.5 ns, respectively.

In order to apply the proposed technique to the conventional edge-combining DLL-based clock multiplier, PRNG, decoders, the matrix switch and branch delay lines are additionally required. However, additional power consumption is only 14.78 μ W (8.94 μ W from the matrix switch and 5.84 μ W from PRNG & decoders). Since only 17 delay cells are turned on for each delay line selection, branch delay lines does not consume any additional power. The layout areas of the matrix switch, PRNG & decoders, and branch delay lines are 0.05 mm², 0.03 mm², 0.182 mm², respectively. Table I summaries the performance comparisons with the state-of-the-art edge combining DLLs.

Fig. 6. Chip layout

Fig. 7. The output spectrum of the proposed clock multiplier

Fig. 8. Phase noise result of rotational DCDL

Table I. Performance summary and comparison with edge-combining DLL

	This work	[9]			[11]	[12]	[13]
Process	180 nm	90 nm			180 nm	350 nm	180 nm
Area	0.608 mm ²	0.04 mm ²			0.15 mm ²	0.601 mm ²	0.043 mm ² *
Supply	1.2 V	1.2 V			1.8 V	3.3 V	1.8 V
Multiplying Factor	16	2	3	6	14	4	313
Output Frequency	16 MHz	1.7 GHz	2.55 GHz	5.1 GHz	1.4 GHz	40 MHz	10 MHz
Reference Spur	−38 dBc	−39.2 dBc	−36.8 dBc	−26.2 dBc	−40 dBc	<i>N.A.</i>	−37.1 dBc
Phase Noise (dBc/Hz)	−83.5 @ 1 MHz	−129.7 @ 1 MHz	−127.4 @ 1 MHz	−121.4 @ 1 MHz	−120.1 @ 1 MHz	<i>N.A.</i>	−100 @ 1 MHz
RMS Jitter	1.76%	<i>N.A.</i>			0.21%	3.5%	2.3%
Power	169.4 uW	20 mW			20 mW	700 uW	42 uW

*exclude off-chip loop filter

4 Conclusion

This paper presents a novel architecture of DLL-based clock multiplier for spur reduction. The rotational DCDL and PRNG based randomized delay line selection technique are proposed to reduce the spurs from delay cell mismatches. In the post-layout verification, the proposed technique achieves 5~11 dB spur level reduction including 6.2 dB improvement from the worst case spur. The proposed clock multiplier is implemented in 0.18 μ m CMOS process, occupies 0.608 mm² and consumes 169.4 μ W for 16 MHz generation.

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