Experimental Verification of Wandering Spur Suppression Technique in a 4.9 GHz Fractional-\(N\) Frequency Synthesizer

Dawei Mai\(^1\), Yann Donnelly\(^3\), Michael Peter Kennedy\(^1\), Stefano Tulisi\(^4\), James Breslin\(^4\), Pat Griffin\(^4\), Michael Connor\(^4\), Stephen Brookes\(^4\), Brian Shelly\(^4\) and Michael Keaveney\(^5\)

\(^1\)School of Electrical and Electronic Engineering, University College Dublin, Dublin, IRELAND, \(^2\)Microelectronic Circuits Centre Ireland, University College Dublin, Dublin, IRELAND, \(^3\)Qualcomm Technologies, Cork, IRELAND, \(^4\)Analog Devices, Limerick, IRELAND, \(^5\)Robert Bosch Ireland Limited, Limerick, IRELAND

Abstract—Apart from the well-known nonlinearity-induced fixed spurs, a DDSM divider-based fractional-\(N\) frequency synthesizer can manifest spurs with time-varying frequency offsets from the carrier; these are called wandering spurs. This paper presents experimental results for a 4.9 GHz CP-PLL fractional-\(N\) PLL featuring a modified MASH-based divider controller that implements wandering spur suppression. The synthesizer achieves a 20 dB reduction in the spectral envelope of the short-term output phase noise spectrum when compared to the standard MASH DDSM divider controller.

I. INTRODUCTION

Fractional-\(N\) frequency synthesizers are widely used as local oscillators and clock generators in a range of applications where frequency resolution and accuracy, as well as spectral purity, are key specifications. Divider-based architectures are commonly used. The divider controller, which is conventionally a digital \(\Delta - \Sigma\) modulator (DDSM), controls the instantaneous division ratio of the multi-modulus divider in the feedback path of a PLL and introduces a quantization error; this contributes directly to the output phase noise [1]. Interactions between the quantization noise introduced by the divider controller and nonlinearity in the loop leads to an elevated inband noise floor and spurious tones (spurs) at well-defined offsets from the carrier [2], [3], so-called fixed spurs.

Apart from the well-understood and predictable fixed spurs, a DDSM divider controller-based fractional-\(N\) frequency can also exhibit spurs that are not fixed in frequency but appear to move about the short-term spectrum. These spurs can protrude above the expected output phase noise profile by 10 to 20 dB and appear at seemingly random offsets and times [4], [5]. For a system that operates with a short time window, e.g., radar, burst communications and precision instrumentation, such time-varying spurs can have significant adverse consequences [6]. Such spurs have been called (amongst others) “marching,” “moving”, “walking” and “wandering” spurs. Since “marching” and “walking” are associated with the measurement instrument—the spectrum analyzer—rather than the phenomenon, we prefer to use the term “wandering spurs” in this paper.

It has been shown that wandering spurs are caused by the DDSM divider controller employed in the synthesizer [7]. Based on analysis of the wandering spur generating mechanism in a MASH 1-1-1 DDSM-based synthesizer, a modified MASH DDSM architecture for the mitigation of wandering spurs was proposed in [8]. In this work, details of the implementation and experimental verification of the wandering spur suppression technique in a 4.9 GHz 180 nm SiGe BiCMOS CP-PLL synthesizer are presented. Wandering spurs are attenuated by more than 20 dB compared to a conventional MASH, with a jitter penalty of just 8 fs.

II. MODIFIED MASH DDSM WANDERING SPUR SOLUTIONS

The wandering spur phenomenon arises in a variety of divider controller architectures when the fractional divide ratio is fixed. We focus on a commonly-used MASH 1-1-1 divider controller in this paper.

The wandering spur generating mechanisms in a MASH 1-1-1-based fractional-\(N\) frequency synthesizer have been studied in [7] and [9]. Wanderings spurs have been classified into three cases based on the input to the MASH 1-1-1 DDSM divider controller. Since the second stage quantization error either contains the underlying pattern or causes the underlying pattern in the third stage quantization error, adding high-amplitude dither \(d_2[n]\) at the input to the third stage error feedback modulator (EFM) in a MASH 1-1-1 can mitigate wandering spurs [8]. This dither signal can be provided by an external source [10] or it can be derived from a signal that is already available in the modulator, without the need for an additional dither generator [8]. Multiple possible modifications of the standard MASH 1-1-1 can eliminate the wandering spurs. In [8], different feedback structures in the third stage EFM were shown to lead to second-order and third-order shaped phase noise contributions of the divider controller.

Fig. 1 shows a modified MASH DDSM comprising three EFM stages and an error cancellation filter. Dither signal \(d_1[n]\) provides first-order shaped LSB dither. The third EFM stage is modified to provide wandering spur suppression. The
where modified MASH can then be expressed as

\[ Y_3(z) = \frac{1}{M} \left( E_2(z) - (1 - z^{-1})E_3(z) + D_2(z) \right), \]

(1)

where \( M \) is the modulus of the quantizer. The output of the modified MASH can then be expressed as

\[ Y(z) \approx \frac{1}{M} \left( X - (1 - z^{-1})^2(1 - z^{-1} - DT(z))E_3(z) \right), \]

(2)

where \( X \) is the constant input.

When \( DT(z) = 0 \), the modified EFM is configured as a standard EFM1 and the architecture is equivalent to a conventional MASH 1-1-1. When wandering spur suppression is enabled, the dither transfer function

\[ DT(z) = 2(1 - z^{-1})z^{-2} \]

(3)

is applied. As explained in [8], this dither transfer function yields a similar in-band noise level to the standard MASH 1-1-1 due to its third-order shaping characteristic.

Compared to the conventional MASH 1-1-1, a multi-bit quantizer is required in the modified EFM stage and the filter buses are wider. The modified MASH has an output range of \([-11, 12]\) versus \([-3, 4]\) for the standard MASH. This leads to a small increase in the in-band phase noise, as we will show.

### III. IMPLEMENTATION DETAILS

#### A. Synthesizer

A block diagram of the synthesizer is shown in Fig. 2. The charge-pump type-II fractional-\( N \) frequency synthesizer is implemented in a 180 nm SiGe BiCMOS process [11]. In addition to programmable up and down current sources, the synthesizer contains a set of binary-weighted current sources to provide a variable bleed current. A quad-core pseudodifferential Colpitts VCO can generate output frequencies from 4 GHz to 8 GHz. Dividers and multipliers are available at the output of the synthesizer for different output ranges. A passive third-order RC loop filter that gives a closed-loop bandwidth of approximately 100 kHz is implemented externally using discrete components. A photomicrograph of the synthesizer is shown in Fig. 3.

![Fig. 1. Implemented 26-bit MASH divider controller with a configurable third stage EFM. Wandering spur mitigation is enabled via SEL.](image1)

![Fig. 2. Block diagram of the implemented fractional-\( N \) frequency synthesizer.](image2)

![Fig. 3. Photomicrograph of the implemented synthesizer.](image3)
DT(z) = 0,
X = 1
(a)

DT(z) = 2(1 - z^{-1}) z^{-2},
X = 1
(b)

DT(z) = 0,
X = M/2, s_1[0] = 1
(c)

DT(z) = 2(1 - z^{-1}) z^{-2},
X = M/2, s_1[0] = 1
(d)

Fig. 4. Measured short-term spectrum and spectrogram of the output phase noise without (left) and with (right) wandering spur suppression.

A. Spectrograms of Output Phase Noise

As a time-varying frequency-domain phenomenon, wandering spurs are best observed using the spectrogram function of a real-time spectrum analyzer. A spectrogram consists of consecutive short-term spectra. In a spectrogram, the horizontal axis and the vertical axis represent frequency and time, respectively, while the amplitude information is represented by different colors.

The measured short-term spectra and spectrograms for representative inputs that lead to prominent wandering spur patterns in a MASH 1-1-1-based synthesizer are presented for the synthesizer without and with wandering spur suppression. According to the analysis in [7], the nonlinearity in a synthesizer leads to wandering spurs in Case I and Case II. In Case III, the MASH 1-1-1-based synthesizer exhibits wandering spurs even if the synthesizer is linear [9]. Therefore, the bleed current is set to zero during the measurements to give the worst phase detector/charge pump linearity in order to make the wandering spurs as prominent as possible. This facilitates the verification of the wandering spur suppression technique since the synthesizer operates with a realistic nonlinear PFD/CP transfer characteristic that is different from the idealized simulation conditions in [7]–[9].

Fig. 4 shows the results for a constant input $X = 1$ (fractional part $1/M$) and input $X = M/2$ (fractional part $1/2$) with a first stage initial condition $s_1[0] = 1$. In each screenshot, the top spectrum is a conventional short-term spectrum at the marker position shown in the spectrogram. These are representative of Cases I and Case III behavior, which have distinct wandering spur generating mechanisms [7], [9].

The measurement results show that the MASH 1-1-1 DDSM-based synthesizer exhibits typical wandering spur patterns in the output phase noise, which are manifest as the V-shaped traces in the spectrogram. An example of the wandering spur in the conventional short-term spectrum is the top figure in the $DT(z) = 0$ and $X = 1$ case. When the wandering suppression technique is enabled (the right column of Fig. 4), the spectrogram becomes wandering spur-free and uniform along the time axis. The short-term spectrum in Fig. 4(b) shows no wandering spurs.

Notice that in the $DT(z) = 0$ and $X = M/2$ case (Fig. 4(c)), the spectrum shows the scenario where multiple spurs arrive at the carrier frequency, leading to significantly higher in-band noise when compared to the $DT(z) = 2(1 - z^{-1}) z^{-2}$ case (Fig. 4(d)).
B. Long-term Output Phase Noise Profile

The long-term output phase noise profile is the conventional method of evaluating a synthesizer’s performance. Due to averaging, wandering spurs are typically not manifest in the output phase noise measurement.

The output phase noise profiles of the synthesizer in the conventional and mitigation modes are shown in Fig. 5. Due to the folding of the high-frequency phase noise contribution in the presence of nonlinearity, the in-band noise of the synthesizer increases by approximately 1 dB when the wandering spur mitigation solution is enabled. This, together with additional high-frequency noise introduced by the modified MASH divider controller, causes the output jitter to increase from 49.4 fs (Fig. 5(a)) to 56.8 fs (Fig. 5(b)).

V. Conclusion

Key performance metrics of the synthesizer with its MASH divider controller configured as a standard MASH 1-1-1 DDSM and as a modified MASH with wandering spur mitigation are compared in Table I. When wandering spur suppression is enabled, the amplitude envelope of the output phase noise short-term spectrum is reduced by more than 20 dB, with a jitter penalty of less than 8 fs. No wandering spur pattern is observed when suppression is enabled.

TABLE I

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Technology (nm)</th>
<th>Supplies (V)</th>
<th>$f_{PED}$ (MHz)</th>
<th>$f_{VCO}$ (GHz)</th>
<th>Loop BW (kHz)</th>
<th>In-band Noise (dBc/Hz)</th>
<th>Noise at 3 MHz (dBc/Hz)</th>
<th>Jitter, 1 kHz-100 MHz (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DT(z) = 0$ (MASH 1-1-1)</td>
<td>180</td>
<td>1.2/3/5</td>
<td>122.88</td>
<td>$\approx 4.9$</td>
<td>100</td>
<td>$-114$</td>
<td>$-143$</td>
<td>49.4</td>
</tr>
<tr>
<td>$DT(z) = 2(1-z^{-1})z^{-2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

REFERENCES