A Low-Noise FBAR-CMOS Frequency/Phase Discriminator for Phase Noise Measurement and Cancellation

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***Abstract*—A sensitive low-noise frequency/phase discriminator and its applications in phase noise measurement and phase noise cancellation are presented. The discriminator uses a high quality factor thin Film Bulk Acoustic Resonator (FBAR) in a notch filter configuration with common-mode traps to reduce the low-frequency noise up-conversion. The performance of the notch filter, the discriminator transfer function, output noise, and phase noise floor are measured and compared with simulations. A feed-back feed-forward phase noise cancellation scheme is proposed based on the frequency/phase discriminator. Two chips were fabricated in 0.13 μm CMOS technology integrating the discriminator and the phase noise cancellation schemes, respectively. The 1.5 GHz discriminator shows phase noise floor of -128 dBc/Hz at 20 kHz, -142 dBc/Hz at 100 kHz, -162 dBc/Hz at 1 MHz and -166 dBc/Hz at 4 MHz, while consuming 26 mW of power. The measured phase noise of the feedback cancellation circuitry reaches the phase noise floor of the discriminator, verifying the proposed concepts.**

***Index Terms*—phase noise, thin Film Bulk Acoustic Resonator (FBAR), frequency/phase discriminator.**

I. Introduction

Generation and measurement of stable frequency sources are at the heart of scientific and engineering systems including time-keeping, navigation, communications, computation, and sensing. High quality factor resonators and low-loss delay elements are essential for sensitive measurements and generation of stable, low phase noise frequency sources as they provide high sensitivity in "discriminating" phase and/or frequency changes. A high-Q resonator or a low-loss delay element can be generally used in two ways to generate or measure frequency sources. First, they can be coupled to a nonlinear active core to create a stable low phase-noise oscillator. This oscillator can then be used as a locking reference for other oscillators or to measure the phase noise. Examples include utilization of crystal oscillator as the reference of Phase Locked Loops (PLLs) and PLL-based phase noise measurement systems [1]. High-Q resonators and low-loss delay lines can also be used to create a frequency and/or phase discriminator, a block that directly measures frequency/phase noise with high sensitivity. Examples include delay line discriminator-based phase noise measurement systems [1] and frequency stabilization techniques [2].

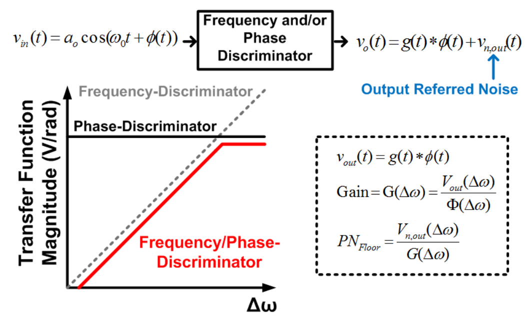

Fig. 1. Ideal discriminator and the related definitions

In this paper, a frequency/phase discriminator based on a thin Film Bulk Acoustic Wave Resonator (FBAR) is presented. Various circuit techniques to maintain low noise and high linearity of the discriminator are also introduced. A feed-back feed-forward phase noise cancellation scheme based on the discriminator is proposed. Extensive measurements validate the conceptual and theoretical claims.

II. Frequency/phase discriminator

A. Discriminator basics

The output voltage of a frequency and/or phase discriminator is a function of its input signal phase modulation (Fig. 1). Phase, frequency or both can be discriminated depending on whether the output signal is proportional to input phase modulation, derivative of phase modulation (frequency modulation) or the combination of the two, respectively. The input-output transfer function of this block can be expressed as

$$v_{in}(t) = a_o cos(\omega_0 t + \phi(t)), \quad (1)$$

$$v_o(t) = v_{out}(t) + v_{n,out}(t), \quad (2)$$

$$v_{out}(t) = g(t) * \phi(t), \quad (3)$$

$$G(\Delta\omega) = \frac{V_{out}(\Delta\omega)}{\Phi(\Delta\omega)}, \quad (4)$$

where $v_{in}(t)$ is the input signal, $v_{out}(t)$ is the output due to the input signal, ω_0 is the input frequency, $\phi(t)$ is the input phase modulation (that can be phase noise), $g(t)$ is the impulse response of the system, $\Delta\omega$ is the offset frequency, and $v_{n,out}(t)$ is the output referred noise of the

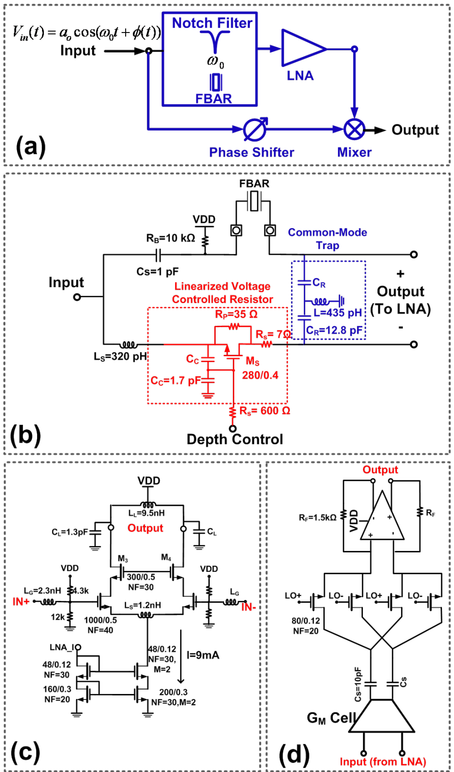

Fig. 2. (a) Block diagram of the frequency/phase discriminator. (b) Schematic of the notch filter (c) Schematic of the LNA (d) Schematic of the mixer

discriminator. The phase-noise floor of the discriminator, also known as its sensitivity, can be written as

$$PN_{floor}(\Delta\omega) = \frac{V_{n,out}(\Delta\omega)}{G(\Delta\omega)}. \tag{5}$$

B. Frequency/phase discriminator design

The proposed frequency/phase discriminator consists of a notch filter, a Low Noise Amplifier (LNA), a mixer, and a phase shifter (Fig. 2.a). Assuming the frequency of the applied signal to the discriminator and the notch frequency are matched, the phase shifter ensures that the inputs to the mixer are in quadrature. It can be shown that, under this condition, the frequency discriminator transfer function is

$$G = \frac{V_{out}(\Delta\omega)}{\Phi(\Delta\omega)} = a_o A_{LNA} A_{Mixer} \frac{\tau j\Delta\omega}{\tau j\Delta\omega + 1}, \tag{6}$$

where ω_0 is the frequency of the notch filter and the input, $\phi(t)$ is the phase modulation of the input signal, A_{LNA} is the LNA gain and A_{Mixer} is the mixer conversion gain, and $\tau = \frac{2Q_L}{\omega_0}$ is the maximum group delay of the notch filter. At low offset frequencies ($\Delta\omega << 1/\tau$), the discriminator output is proportional to the derivative of the phase (frequency), and at high offset frequencies ($\Delta\omega >> 1/\tau$), it is proportional to the phase itself. Higher quality factor leads to higher transfer gain and sensitivity.

Figure 2.b shows the schematic of the notch filter. The FBAR used in this circuit has a series resonance frequency of 1.488 GHz with a corresponding quality factor of 1500 [7]. The DC voltage applied to the voltage controlled resistor balances the loss between the two branches of the notch, thereby controlling the depth of the notch. Coupling capacitors, C_c, couple some of the swing at the source of M_s to its gate and improve its linearity. Capacitor C_s shifts the resonance frequency of the top branch and increases its resistance at resonance. The use of the inductor L_s is to ensure that the group delay maximum is achieved at the notch frequency. All the active circuits in a sensitive, low-noise discriminator must be linear to avoid up-conversion of low-frequency noise to around the center frequency [2]. As such, a common-mode trap is used to suppress the common-mode input to the LNA further by creating a short at common mode, without affecting the differential mode operation. The LNA is an inductively degenerated cascode amplifier with tuned load (Fig 2.c). Passive mixer is used for superior flicker noise performance (Fig 2.d). The phase shifter is a simple RC filter.

III. Simulation and Measurement Results

Figure 3.a shows the photograph of the chip wirebonded to the FBAR. The chip has an area of $1.8\ mm \times 1.2\ mm$, is fabricated in an IBM 0.13 μm RF CMOS technology, and consumes 26 mW. Figure 4 shows the simulated and measured S-parameters of the notch filter and LNA when the outputs of the LNA are combined using a 50 Ω off-chip hybrid. Maximum measured group delay of 130 ns enables sensitive discrimination of phase noise. Figure 5 shows the measured and simulated phase to voltage transfer function of the discriminator when the input frequency is matched with the notch filter frequency (and the quadrature point ensured by manually adjusting the phase shift) and also when the frequency is off by 1 MHz and 2 MHz. The E8257C Agilent signal generator with 8 dBm of power is FM modulated and used as an input and the discriminated tone is measured at the output of the discriminator. Notice that, as expected from (6), the discriminator is acting as a frequency discriminator at frequencies below $1/\tau = 1.2MHz$ and a phase discriminator above that frequency. Phase noise floor (sensitivity) of the frequency/phase discriminator is measured using the cross-spectrum technique (Fig. 6) [3]. The measured output of each path consists of the discriminated phase noise of the input signal generator, $C_n(t)$, added to the inherent noise of the discriminator and following components. Given independent paths, the latter noise contributions, $a_n(t)$ and $b_n(t)$, are uncorrelated; but, have the same Power Spectral Density (PSD). The PSD of the difference of the two

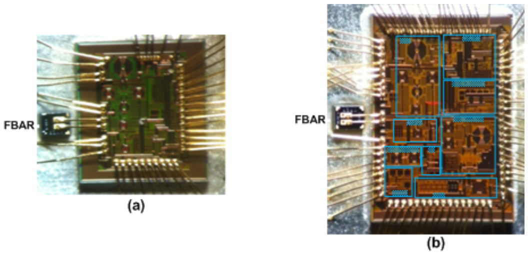

Fig. 3. Photographs of the (a) frequency/phase discriminator and (b) phase noise cancellation scheme.

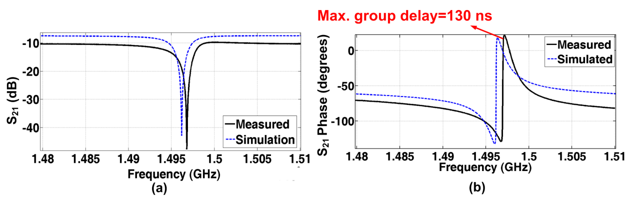

Fig. 4. Notch-filter and LNA combined S-parameters.

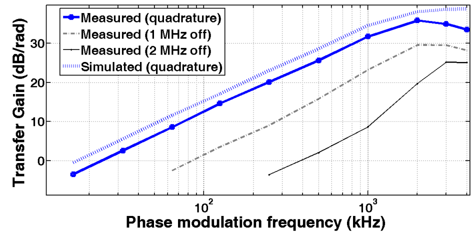

Fig. 5. Phase to voltage transfer curve of the frequency/phase discriminator.

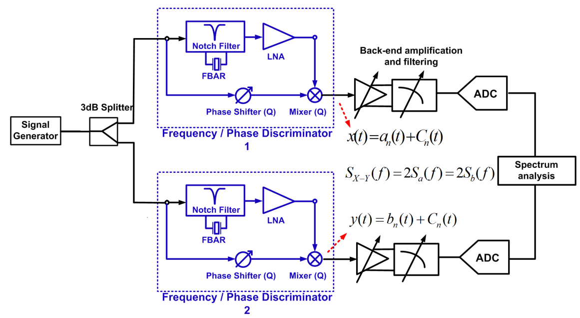

Fig. 6. Discriminator output noise measurement setup.

outputs will be twice the PSD of each discriminator noise, and the signal generator discriminated phase-noise will be canceled. Also, by applying cross-correlation, the noise of the discriminators can be reduced to find the correlated noise. Digital signal processing adjusts for mismatches in the discriminators to suppress the effect of signal generator phase noise on the noise measurement. Figure 7 shows the measured output noise PSD of the two discriminators (at the quadrature point), the normalized PSD of the subtracted outputs (at quadrature and when the input frequency is 2 MHz off from the notch filter frequency), and the cross-correlated PSD of the output noise of the two discriminators with 1000 times averaging. At low offset frequencies, the PSD of the subtracted outputs is lower than the PSD of each output PSD, indicating the dominance of correlated noise at these frequencies. The increase in output noise PSD when the input frequency is off is due to increased low-frequency noise up-conversion in the LNA as the input to the LNA is large signal. The phase-noise floor of the discriminator can be derived from Fig. 5 and Fig. 7 based on eqn. (5) and assuming the power incident to the discriminator is 8 dBm (Fig. 10). Table-1 compares this phase noise floor with the phase noise of different low phase-noise oscillators.

IV. Phase Noise Cancellation

The low-noise frequency/phase discriminator can be used to reduce the phase noise of an oscillator in feedback [2] and/or feedforward configurations. It has been shown that the lowest achievable phase noise in an oscillator is determined by the phase noise floor of its discriminating component which is typically a high-Q resonator [7]. However, given the large signal operation of the oscillator, low-frequency noise is often up-converted to around the oscillation frequency [2], prohibiting reaching the resonator-limited phase noise floor. The proposed discriminator is specifically designed to eliminate the noise frequency up-conversion and enable reaching close to the FBAR-limited phase noise floor. The schematic of the proposed feedback-feedforward phase noise cancellation scheme that utilizes

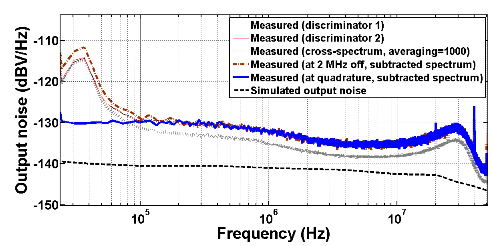

Fig. 7. PSD of the frequency/phase discriminator output noise.

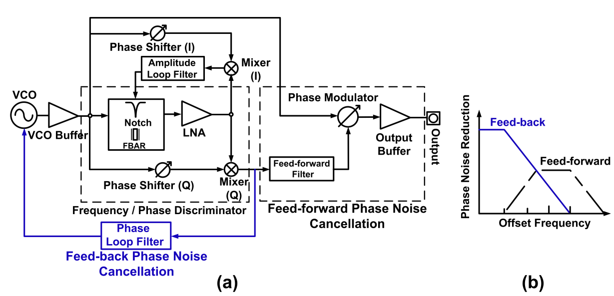

Fig. 8. (a) Feed-back feed-forward phase noise cancellation scheme. (b) phase noise cancellation profile.

TABLE I
Comparison with low phase noise oscillators

	Resonator	Frequency (GHz)	PN @ 1 kHz	PN @ 10 kHz	PN @ 100 kHz	PN @ 1 MHz	PN @ 4 MHz	Power (mW)
Freq./phase Discriminator	FBAR (Q_{series}=1500)	1.5	-	-122	-142	-162	-165.5	26
PN cancellation	FBAR (Q_{series}=1500)	1.5	-90	-120	-137	-141	-136	350
[7]	FBAR (Q_{series}=1500)	1.5	-100	-125	-145	-145	-160	40
[5]	FBAR (Q_{series}=1500)	0.6	-100	-130	-149	-152	-152	5.3 (w/o buffer)
[4]	FBAR	2.6	-81	-107	-130	-155	-155	30
[2]	Air dielectric cavity Q=200000	10	-160	-170	-	-	-	Output power=28 dBm
[6]	Sapphire dielectric Q=200000	10	-125	-145	-	<-160	<-160	-

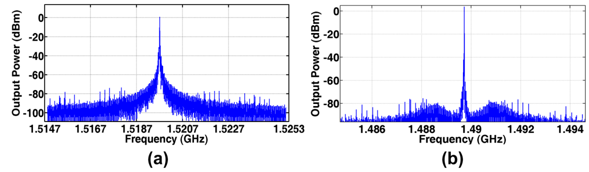

Fig. 9. Output spectrum of the phase noise cancellation scheme (a) before locking and (b) after locking.

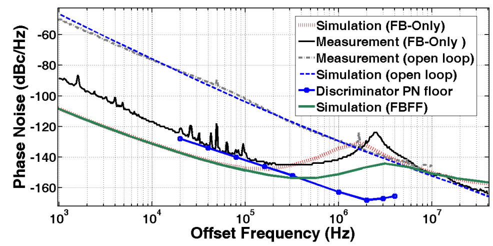

Fig. 10. Phase noise floor of the frequency/phase discriminator and phase noise of the phase noise cancellation scheme.

the frequency/phase discriminator of Fig. 2 is shown in Fig. 8. In this scheme, the discriminator measures the phase noise of a Voltage Controlled Oscillator (VCO) and feeds it back to its control voltage through a phase loop filter. This feedback loop serves two purposes. Firstly, the VCO frequency will be locked to the notch frequency set by the FBAR, and secondly, the phase noise will be reduced inside the loop bandwidth down to the discriminator phase noise floor as conceptually shown in Fig. 8.b. A second loop consists of the mixer (I), phase shifter (I), and an amplitude loop filter. Under locked condition, the two inputs to mixer (I) are in phase. The mixer (I) output signal is proportional to LNA output swing and is fed-back to the notch filter voltage-controlled resistor to control the depth of the notch. The operation of this loop is essential to the performance of the discriminator, since the depth of the notch indicates the swing at the LNA input.

A feedforward path is added to extend the range of phase noise cancellation beyond the feedback loop bandwidth. The function of the feedforward filter is to reconstruct the phase noise by inversing the discriminator transfer function (eqn. (6)). The output of this filter will then modulate the phase of the output through the phase modulator to reduce phase noise over an extended offset frequency range (as shown in Fig. 8.b). Notice that by inversing the discriminator transfer function, the cancellation bandwidth is extended beyond the notch bandwidth. The loop filters are implemented as active RC filters and the phase modulator is implemented as a 90^o T-section phase shifter with a varactor used for modulation.

The entire system, including the VCO, is implemented in a 2×3 mm^2 CMOS chip and consumes 350 mW (Fig. 3.b). Figure 9 shows the chip output spectrum before and after locking. The chip shows a 12 MHz locking range and 25 MHz tracking range. Figure 10 shows the simulated and measured phase noise of the stand-alone VCO and the feedback cancellation with feedforward simulations. As expected, the output phase-noise, within the loop bandwidth, reaches the phase noise floor of the discriminator. Phase noise at higher offsets can be reduced by the feedforward path.

V. Conclusion

In this paper, integrated implementation of a low phase noise frequency/phase discriminator using an FBAR resonator is presented. It is shown that this discriminator can be used for phase noise measurement and stable frequency generation. A feed-back feed-forward phase noise cancellation scheme is proposed that reduces the inherent phase noise of an oscillator to that set by the resonator in the frequency/phase discriminator.

Acknowledgment

This work was partially supported by the Office of Naval Research (ONR) Electronic Warfare Discovery and Invention Program.

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