Measurement of AM-to-PM Conversion in a Quartz-MEMS Resonator

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***Abstract*— This work investigates the new aspects of the non-linear response in a quartz-MEMS resonator at 635 MHz. We characterize its major cause of AM-to-PM conversion as a function of power and drive frequency; this is important in developing noise compensation schemes.**

***Keywords*— AM-to-PM conversion; phase noise; resonator; Quartz-MEMS**

I. Introduction

A characteristic of resonators that operate with high drive levels and are driven into non-linearity is the loss of orthogonality between normally orthogonal amplitude modulation (AM) and phase modulation (PM). Thus, an AM-to-PM conversion occurs that can substantially increase the PM noise. To reduce PM-noise due to this conversion, we can detect the AM fluctuations versus a DC reference and use these fluctuations to control PM fluctuations. This paper focusses on characterizing the AM-PM conversion.

Quartz resonators operating at high-order modes have widespread applicability. Quartz fabrication and mounting technology consistently rank highest in terms of size, weight, power, cost, high-Q, high power 'linear' response and environmental insensitivity, especially at resonant frequencies below 100 MHz. As the quartz oscillator frequencies go higher (above a 100 MHz and approaching a few gigahertz) in most applications, the use of quartz as the frequency-determining element yields reduced Q and linearity to sustain low phase noise.

II. Characterization Of A Quartz-MEMS Resonator[1]

We explore non-linear effect in a quartz-MEMS resonator at 635 MHz [1]. The magnitude and phase of the s-parameter S_{21} are measured on a vector network analyzer as shown in Fig. 1. The s-parameter indicates that the resonator moves into a nonlinear region known as the Duffing regime of operation with increasing power. We also see hysteresis when the frequency is swept in the reverse direction only for higher input power to the resonator. This effect is displayed in the inset of Fig. 1.

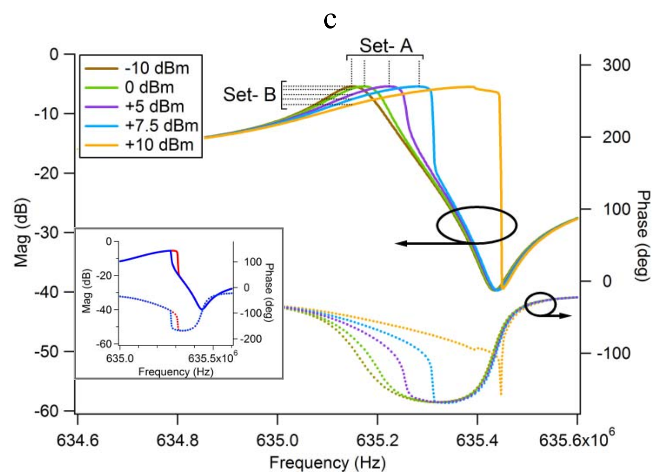

Fig. 1. Measured data of S_{21} (magnitude and phase) of the Quartz MEMS resonator for different input power levels. The inset shows the hysteris effect for forward and reverse freqeuncy sweep at +7.5 dBm input power.

A asymmetry in the resonator frequency response can cause correlation between AM and PM noise. To observe this effect, we used the measurement configuration shown in Fig. 2.

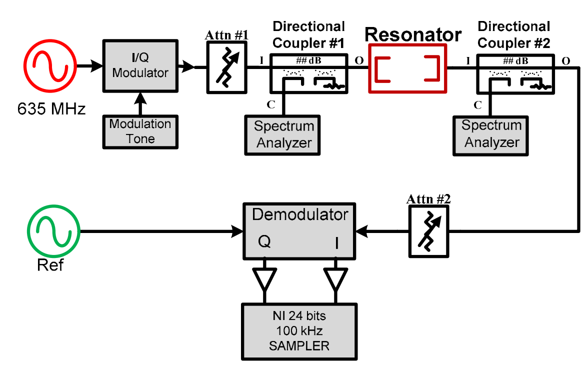

Fig. 2. Experimental set-up for the measurement of AM-to-PM conversion in the quart-MEMS resonator (DUT) at 635 MHz.

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A 635 MHz low noise signal from a frequency generator is amplitude modulated using an I/Q modulator and applied to the resonator. The I/Q modulator is carefully set-up to generate pure AM modulation; under this condition the residual PM modulation is less than 40 dB below the AM modulation. This pure AM modulated signal is monitored on a spectrum analyzer at the input and output port of the resonator. In Fig. 3, we can see a symmetric spectrum at the input of the resonator, while at the output we get a asymmetry in the upper and lower sidebands. The asymmetric spectrum at the output implies a portion of the AM is converted to PM when the resonator is operating in its non-linear (Duffing) regime. In addition to measuring the input and output spectra of the resonator, we also measured the level of the detected AM and PM tone using I/Q demodulation. As shown in Fig. 4, when the input power is low the conversion of AM-to-PM is low, and for larger input power when the resonator is in the Duffing regime the conversion grows to greater than unity. The resonator is also driven at 1 kHz and 10 kHz above and below the resonant frequency for each input power. The result shows that the conversion of AM-to-PM is larger at frequencies above the resonant frequency.

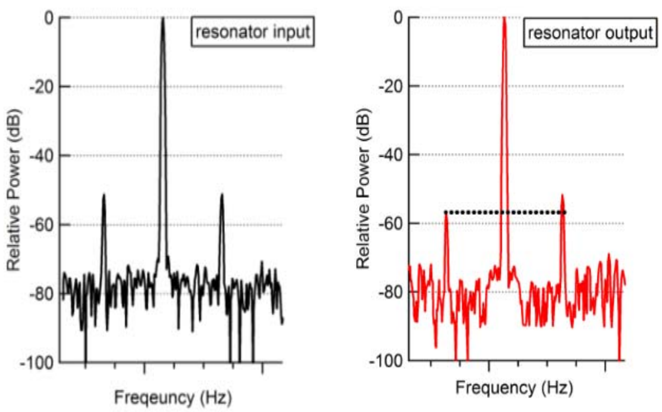

Fig. 3. Spectra of the AM modulated signal before and after the resonator at 635.3 MHz. At the output of the resonator the sidebands are asymmetric. Input power of the resonator = +7.5 dBm, insertion loss = 6.7 dB, modulation frequency = 100 Hz.

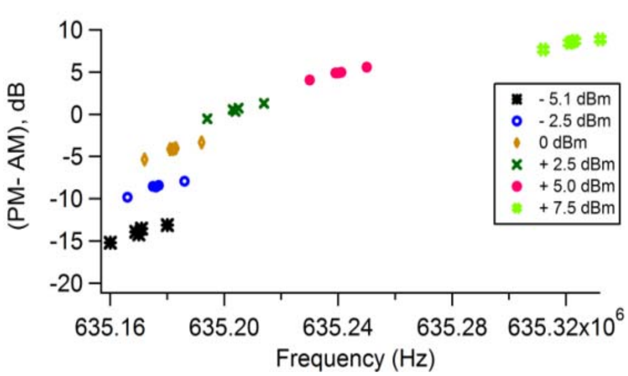

Fig. 4. Amount of AM-to-PM conversion in the quartz-MEMS resonator for different input power. Modulation frequency = 100 Hz.

III. Residual Phase Noise Measurements

Next, we measured the residual noise of the resonator for different input power levels using an analog cross-spectrum phase noise measurement system [2]. The conventional technique for resonator residual noise measurement is described in [3], [4]. Due to the unavailability of two similar resonators at 635 MHz we used the configuration as shown in Fig. 5. The delay (τ) is roughly matched with the delay introduced by the resonator and the amplifier for the residual measurement. The effect of unmatched delay on the phase noise was observed above 10 kHz offset frequency but the close-to-the-carrier noise as shown in Fig. 6 is unaffected by mismatched delay. Two sets of residual measurements are performed. First, the residual noise is measured for different input power at the minimum insertion loss (IL) points indicated by Set-A in Fig. 1. The results of this measurement are displayed in Fig. 6. It indicates that the phase noise of the resonator degrades significantly at higher resonant frequencies when a large input power is applied.

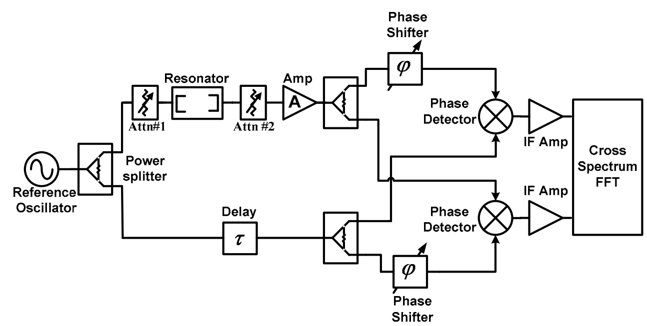

Fig. 5. Experimental set-up for the resonator residual phase noise measurement: Analog configuration. Noise contribution of the amplifier 'A' to the resonator is negligible.

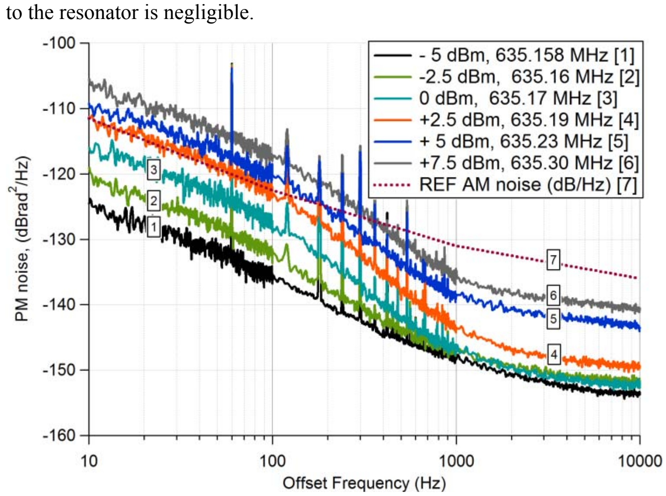

Fig. 6. Residual PM noise of the resonator at the minimum insertion loss point (Set-A) as a function of input power.

However, if we consider the AM noise of the reference oscillator (shown by the dashed line in Fig. 6) at 100 Hz offset and compensate for the AM-to-PM conversion sensitivity for different input power from Fig. 4, we almost get the measured PM noise of the resonator at this offset. This clearly indicates that at 100 Hz offset, the PM noise is mostly due to the AM-to-PM converted noise occurring in the resonator. It is our interpretation that below 200 Hz offset, the measurement of the PM noise is biased due to AM-to-PM conversion and at higher offset frequencies it is actually the PM noise of the resonator.

In a second measurement, i.e., Set-B of Fig. 1, the frequency of the reference is kept fixed at one frequency (635.17 MHz) and the residual noise as shown in Fig. 7 was measured for different input powers. The residual phase-noise of the resonator at 635.17 MHz shows that as the input power increases the PM noise degrades at first and then reduces for power greater than 0 dBm. For all these residual noise measurements, the input power of the amplifier 'A' and the LO and RF power of the phase detectors were kept constant while the input power of the resonator was varied.

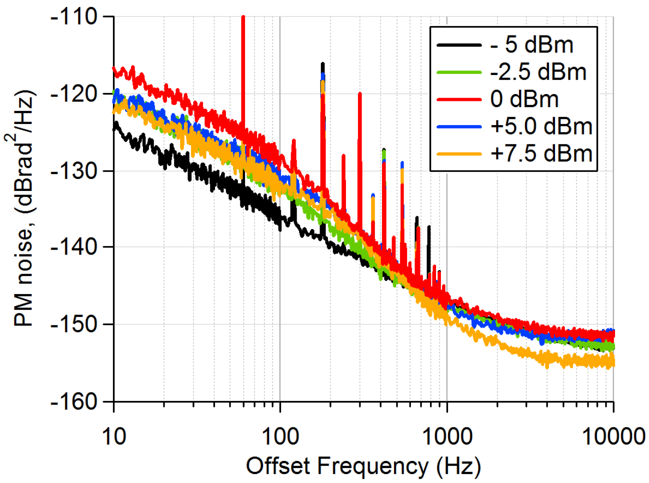

Fig. 7. Residual PM noise of the resonator for varying input power but at a fixed frequency of 635.17 MHz (Set-B). Note that for low input power the resonator shows f^{-1} slope from 10 Hz to 1 kHz, however, for higher input power, the noise slope is f^{-2} between 100 Hz and 1 kHz, indicating non-linearity in the resonator.

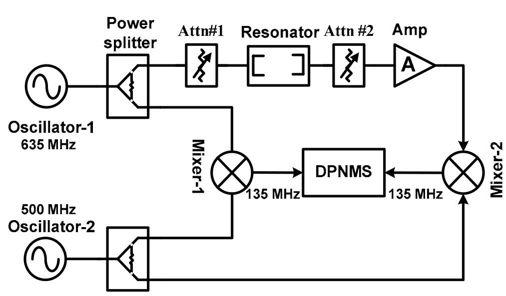

Fig. 8. Experimental set-up for the resonator residual phase noise measurement: Digital configuration. Noise contribution of the amplifier 'A' to the resonator is negligible.

We also implemented a different technique that uses a digital phase noise measurement system (DPNMS) [5] to measure the residual noise of the resonator. This scheme as shown in Fig. 8 uses two mixers for down-conversion of a 635 MHz signal to 135 MHz after mixing with a low phase noise 500 MHz signal. The down-conversion is necessary to bring the signal within the operating range of the measurement system. The results of digital scheme agrees within 2 dB of the analog measurement below a 1 kHz frequency offset, but above 1 kHz the measurement is limited by the system noise floor.

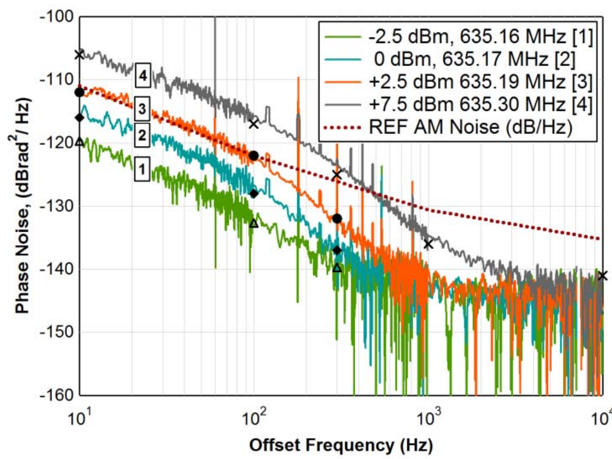

Fig. 9. Residual PM noise of the resonator at the minimum insertion loss point (Set-A).
Solid lines: Noise measured with digital configuration (Fig. 8).
Symbols (Δ♦•×): Noise measured with analog configuration (Fig. 5).

IV. PM-AM Correlation In A Quartz-Mems Oscillator

After characterizing the resonator and the amplifier 'A', we built an oscillator as shown in Fig. 10. The input and output power of the resonator inside the loop is adjusted using variable attenuators 1 and 2. The residual PM noise of the resonator can be used to predict the phase noise of an oscillator using Leeson's model [6], [7] given by

$$S_\varphi(f) = \left[1 + \frac{1}{f^2}\left(\frac{\nu_0}{2Q_L}\right)^2\right] S_\psi(f), \qquad (1)$$

where, $S_\psi(f)$ represents the phase noise of the loop components. In our case the dominant source of noise is the resonator whose loaded quality factor (Q_L) is approximately 5200. The amplifier 'A' in series with the resonator has gain, noise figure, and 1 dB compression power of 20 dB, 4 dB and 18 dBm, respectively. The phase noise of the amplifier at 1 Hz offset is -132 dBrad²/Hz.

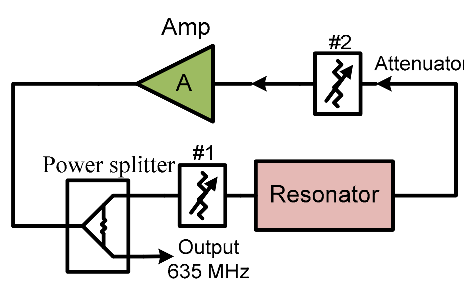

Fig. 10. Block diagram of the oscillator at 635 MHz with control circuit.

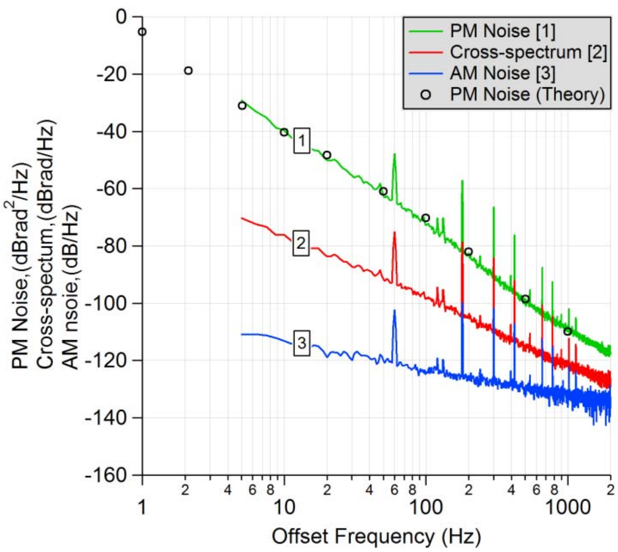

Fig. 11. Plot of double-sideband PM noise, AM noise and cross-spectrum between them for quartz-MEMS oscillator at 635.17 MHz. PM noise of the oscillator predicted from Leeson's model (6) at Pin-res ≈ 0 dBm is represented by black circles.

The PM noise of the oscillator was measured for different input powers and compared with the predicted noise obtained from Fig. 6 and Leeson's model (1). The PM noise shown in Fig. 11 corresponds to the condition when the input power to the resonator is approximately 0 dBm. We see close agreement between the measured and predicted PM noise. In addition to the PM noise, the AM noise and the cross-spectrum between PM and AM noise of this oscillator at 635.17 MHz is also shown in Fig. 11. It is interesting to see that close to-carrier cross-spectrum is exactly the expected geometric mean, even for very widely differing levels of PM and AM noise. This means that substantially complete correlation exists for this quartz-MEMs resonator based oscillator.

V. Conclusion

We have presented the results of AM-to-PM conversion as a function of power and drive frequency in a quartz-MEMS resonator. We also provided schemes for the measurement of a resonator's residual PM noise. We have previously demonstrated that this information is important when developing noise compensation schemes [8], [9] .

Acknowledgement

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