RELATIONSHIP BETWEEN AMPLITUDE AND RESONANT FREQUENCY IN QUARTZ CRYSTAL RESONATORS♦

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ABSTRACT

In this paper we report results of measurements on the resonant frequency of crystal resonators as a function of drive current (amplitude). Previous studies indicate that the resonant frequency increases as the square of the driving current. If we assume that the limiting factor in the flicker frequency noise of crystal resonators is the noise in the drive current, then the quadratic dependence suggests that crystal resonators should be driven at low current for better frequency stability. Frequency versus amplitude measurements were made on SC-cut, 5th overtone, 100 MHz crystal resonators using a network analyzer. As expected, the measurements show a general quadratic dependence of frequency versus drive current. Nevertheless, some crystals exhibit phase (frequency) jumps at certain drive currents and certain temperatures. Phase modulation (PM) noise measurements were made in test oscillators at several currents to see if there is a correlation between the amplitude-frequency effect and flicker of frequency noise. Our results indicate that the flicker of frequency noise varies with current, but the current at which the flicker of frequency noise is the lowest is not necessarily the lowest current (as the quadratic relation of ν_o versus drive current suggests).

INTRODUCTION

The goal of this research was to investigate in fine detail the frequency of 100 MHz quartz resonators as a function of crystal drive. It has long been known that the resonant frequency of quartz resonators depends slightly on the level of excitation [Gagnepain and Besson (1), Gagnepain (2), Kusters (3), Tiersten (4), Filler (5)]. This effect is commonly called the amplitude-frequency effect. The data and analysis of Kusters (3), Filler (5), and others indicate that the frequency depends (approximately) quadratically on crystal current. Several questions arise. Is the curve smooth, or are there jumps in crystal frequency? Is the frequency monotonic with increasing crystal current, or is there an extremum at some low current? If there is an extremum, how does this affect the flicker of frequency noise? If there are jumps how do they affect the flicker of frequency noise?

We made this study at 100 MHz because the resonators are less expensive than 5 or 10 MHz resonators. They are also smaller which allows for more resonators to be made from a given quartz bar. Furthermore, the flicker of frequency noise of such resonators should be less dependent on temperature fluctuations than 5 or 10 MHz resonators because the fractional flicker of frequency noise in the 100 MHz resonators is approximately 20 dB higher than in comparable 10 MHz resonators. The general characteristics of the resonators reported in this study are given in Table 1. All resonators were cut from the same bar of synthetic, unswept quartz, and fabricated with the manufacturer's standard polishing, electrode size, and electrode deposition techniques. Later studies will examine the effect of changing electrode size, polishing technique, dislocation density, and sweeping on the amplitude-frequency effect and flicker of frequency noise [Ferre-Pikal et al., (6)].

TABLE 1. General characteristics of crystal resonators.

Crystal Resonators used in this Study	
Frequency	100 MHz
Overtone	5th
Blank diameter	6.3 mm
Blank thickness	90 µm
Electrode Diameter	3.05 mm
Geometry	plano-plano
Turnover temperature	60 - 72 °C

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MEASUREMENT OF THE AMPLITUDE-FREQUENCY EFFECT AT 100 MHZ

Figure 1 shows the measurement technique used to determine the amplitude and phase of the signal transmitted through the resonators at series resonance. The variable capacitor is used to cancel the holder capacitance of the resonator.

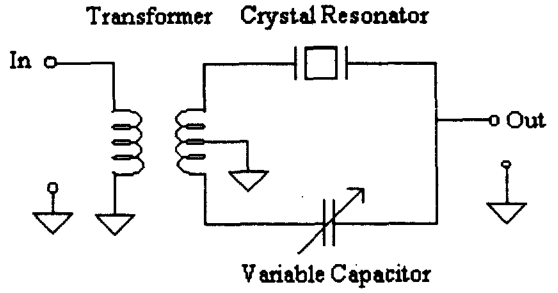

Figure 1: Technique used to measure the amplitude and phase of the transmitted signal through the resonators.

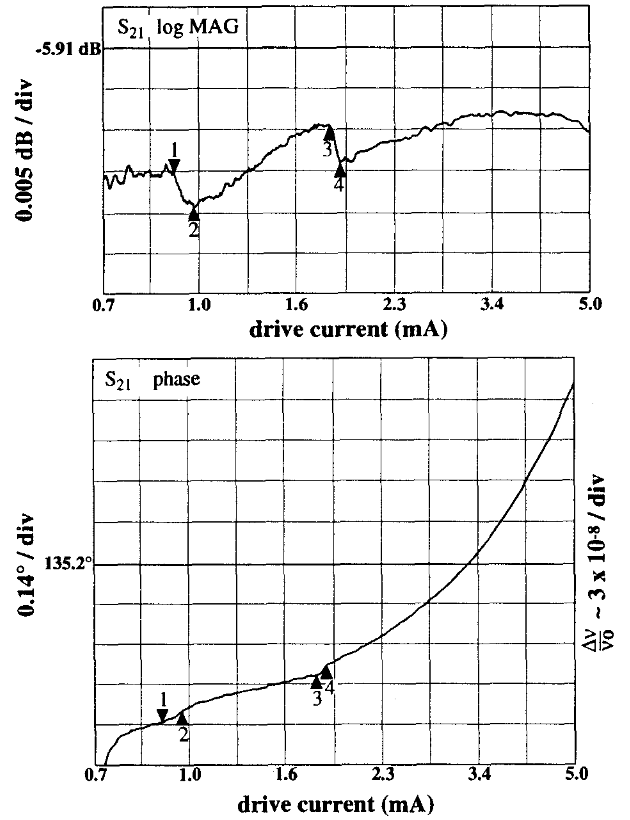

Figure 2: Amplitude and phase for the transmitted signal in resonator 2. The fractional frequency axis in the phase plot was calculated assuming a loaded Q (Q_L) of 0.4 x 10^5 and using the relation $\Delta\nu/\nu_o = \Delta\phi/(2Q_L)$ [7].

The upper part of Fig. 2 shows the amplitude of the transmitted signal for resonator 2 at the frequency-temperature turnover point. The vertical scale is 0.005 dB per division. The horizontal scale is linear in drive current squared. The left corner (origin) corresponds to approximately 0.7 mA, while the right corner approximately corresponds to 5.0 mA. Two step changes in the transmitted amplitude are clearly visible. The lower trace shows the phase shift across the resonator as a function of drive current. Changes in the phase shift across the resonator lead to frequency changes in the oscillator [Leeson, (7)], therefore the approximate quadratic dependence of phase on drive current translates into quadratic frequency dependence on drive current. [The initial increase in phase is due to startup effects in the resonator.] The markers are at the same position as in the upper trace. The phase steps are not as easily seen as in the upper trace (magnitude changes), but nonetheless are visible.

In Fig. 3 we compare the magnitude of the transmitted signal in resonator 2 at 20°C and 65°C. Clearly there is significant change in the current at which the jumps occur between 20°C and 65°C in this resonator.

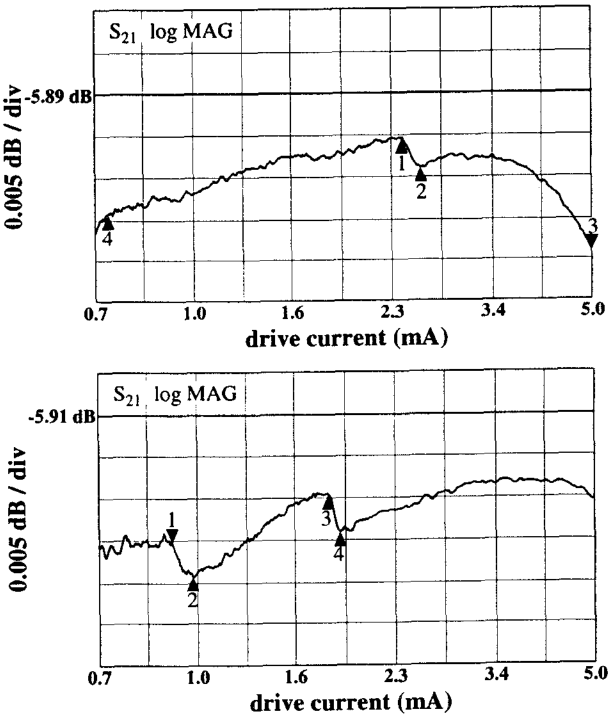

Figure 3: Magnitude of the transmitted signal in resonator 2 at 20°C (upper plot) and 65°C (turnover temperature) (lower plot).

In Fig. 4 we show the amplitude and phase for resonator 15 at 20°C. The upper trace clearly shows an abrupt jump in amplitude between markers 1

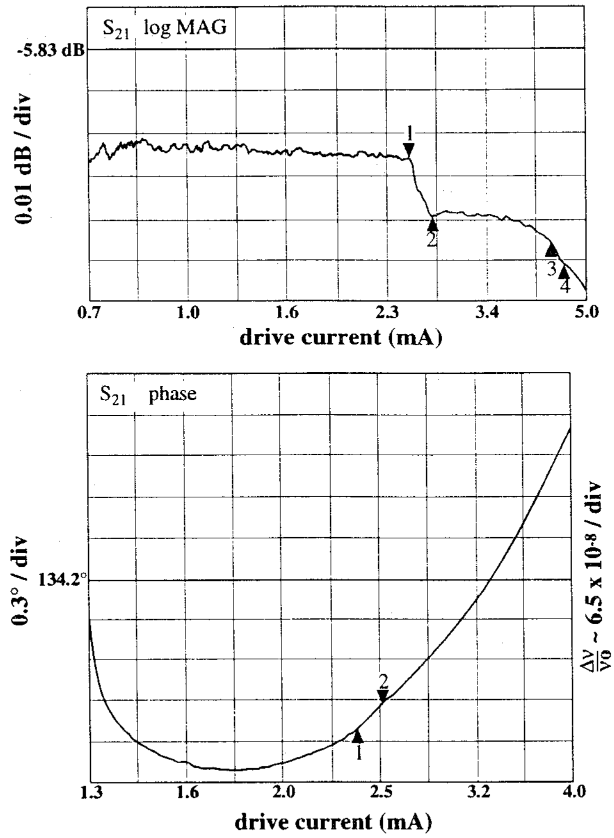

Figure 4: Magnitude and phase of the transmitted signal for resonator 15 at 20°C. The fractional frequency axis in the phase plot was calculated assuming $Q_L = 0.4 \times 10^5$.

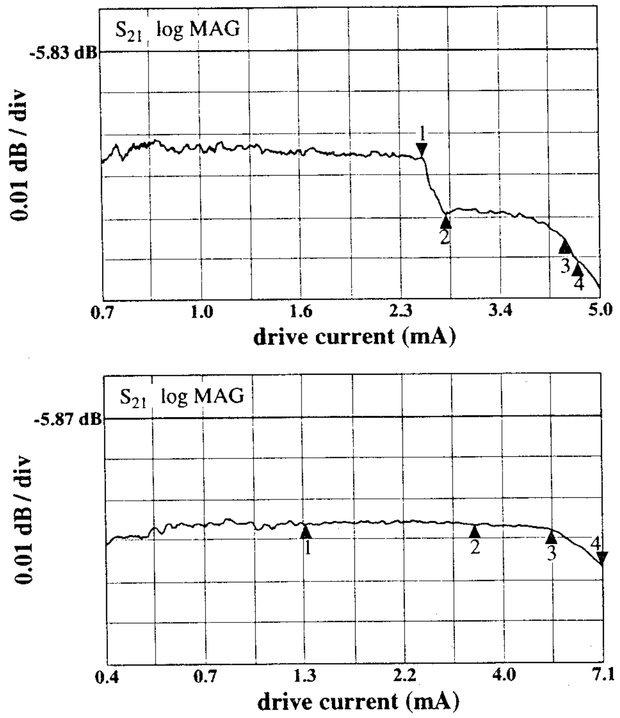

Figure 5: Amplitude of the transmitted signal in resonator 15 at 20°C (upper plot) and 72°C (lower plot).

and 2. The lower trace, however, does not show a corresponding jump in the phase.

In Fig. 5 we compare the amplitude of the transmitted signal in resonator 15 at 20°C and the frequency-temperature turnover point. At turnover no jumps are apparent. [The initial drop in phase is due to startup effects in the resonator.]

A survey of 12 resonators made from the same quartz material at the same time by the same manufacturer yielded 6 resonators with jumps in the transmitted signal at either room temperature or at turnover point.

MEASUREMENT OF PHASE MODULATION (PM) NOISE VERSUS DRIVE CURRENT

Figure 6 shows the block diagram of the cross-correlation technique used to measure the PM noise of the test resonators incorporated into test oscillators [F.L. Walls (8), W.F. Walls (9)]. This approach provides a noise floor for measuring the PM noise of the test oscillator which is at least $\mathcal{L}(10\ \text{Hz}) = -118$ dBc/Hz [10]. So far this is below that of any of the resonators tested. The PM noise in the 100 MHz crystal oscillators was measured at Fourier frequencies of 5 to 200 Hz, where the PM noise exhibits flicker of frequency noise (f^{-3} power law). Here we use $\mathcal{L}(10\ \text{Hz})$ as an indication of the magnitude of the flicker of frequency noise in different resonators.

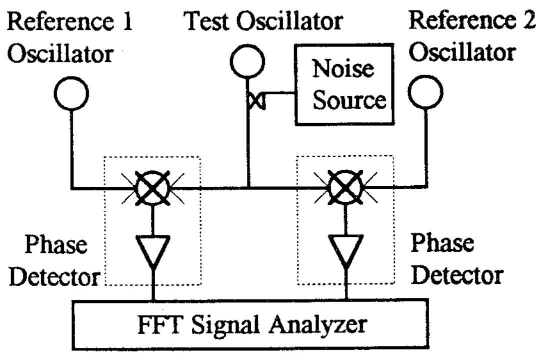

Figure 6: Block diagram of the cross-correlation PM noise measurement system

In Fig. 7 we show $\mathcal{L}(10\ \text{Hz})$ for resonator 2 measured in a test oscillator as a function of crystal drive current. The arrows show the direction of the changes in crystal drive. There is a definite change in $\mathcal{L}(10\ \text{Hz})$ with crystal drive and a very clear

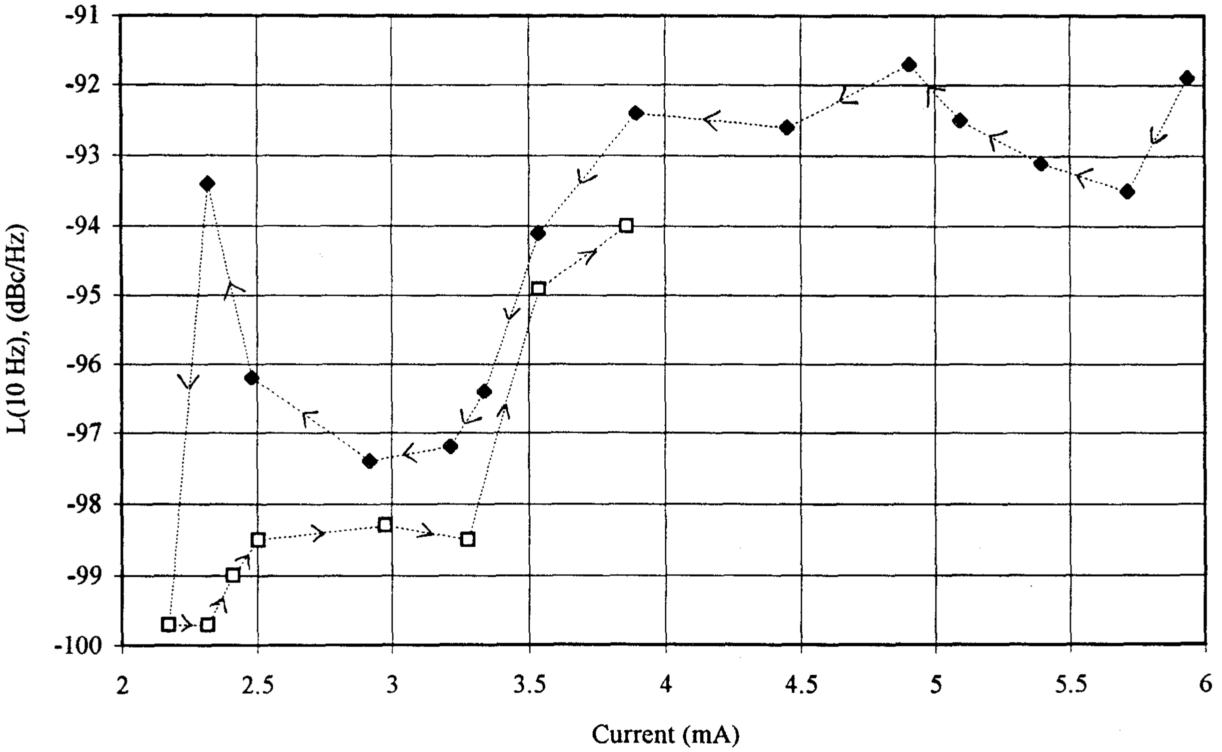

Figure 7: ℒ(10 Hz) of resonator 2 as a function of drive current

hysteresis of ℒ(10 Hz) versus direction of change in in crystal current. Referring to Fig. 2, the hysteresis occurs close to the point of the upper jump in the transmitted amplitude. In general, the flicker of frequency noise changed considerably with drive current. Measurements of ℒ(10 Hz) versus crystal current for all 12 resonators are shown in Fig. 8, trace labeled "Initial".

We also considered the effect of baking the resonators on the flicker of frequency component of the PM noise. After initially measuring the flicker of frequency noise (ℒ(10 Hz)) at several drive currents, the resonators were baked at 90°C for approximately 2 days and then baked at 100°C for at least 3 more days. Measurements after baking show substantial improvement in some resonators and no effect in others. See Fig. 8, where the trace labeled "Initial" refers to the initial ℒ(10 Hz) measurements, and the trace labeled "Tmin" refers to ℒ(10 Hz) after baking the resonator at the current with best noise performance. For example, ℒ(10 Hz) of R1, R3, R11, and R13 improved considerably when baked. Most of the changes in the flicker of frequency noise occur in the first 2-3 days of the baking cycle. After baking, the number of resonators with ℒ(10 Hz) less than -100 dBc/Hz was 9 (out of 12). The effect of baking the resonators at high currents (6 mA) was also investigated (trace "T@HI", Fig. 9), but there was not a strong indication that this had an effect on flicker of frequency noise.

Table 2 shows ℒ(10 Hz) of the resonators at 100°C and at the frequency turnover. It is quite surprising that the ℒ(10 Hz) at 100°C is equal or better that the ℒ(10 Hz) at the turnover temperature (for 9 out of 12 resonators) since at 100°C the frequency changes very rapidly with temperature.

TABLE 2. Comparison of ℒ(10 Hz) at turnover temperature and at 100°C for crystal resonators.

Resonator #	Current (mA)	ℒ(10 Hz) (dBc/Hz) Turnover	ℒ(10 Hz) (dBc/Hz) 100°C
R1	2.8	-102.8	-100.8
R2	2.2	-95.1	-96.2
R3	4.5	-95	-98
R4	2.8	-96.6	-98.4
R5	2.7	-101.3	-101.2
R6	2.8	-106.5	-106
R11	2.4	-100.4	-103.2
R12	3.5	-102.0	-94
R13	2.9	-102	-104
R14	3	-111	-110.3
R15	2.7	-101.6	-104.1
R16	2	-102.3	-102

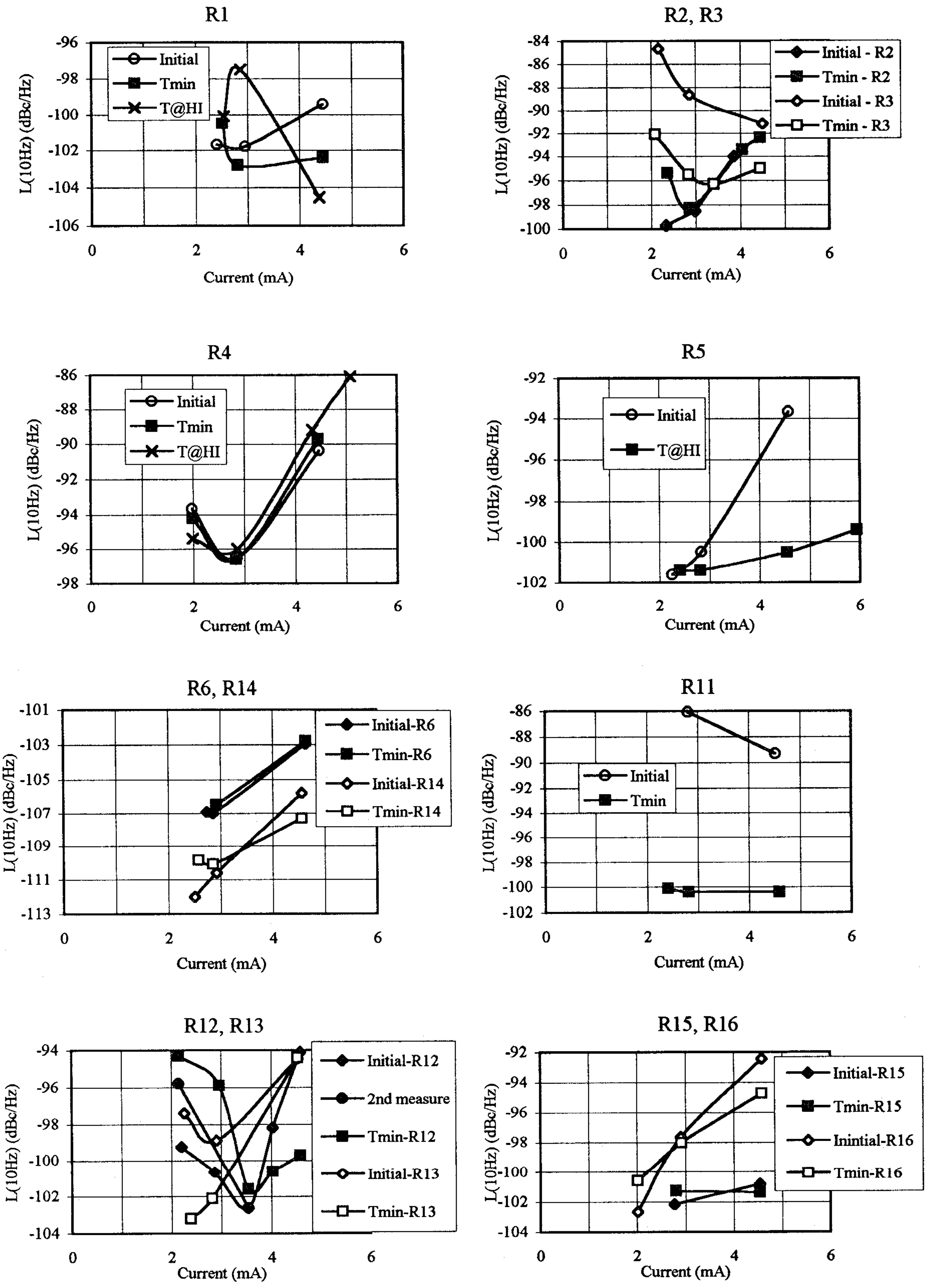

Figure 8. L(10 Hz) for crystal resonators as a function of drive current

DISCUSSION AND CONCLUSION

This study shows that the amplitude-frequency effect is very complicated in some resonators. These units show features that are not explained by a simple quadratic dependence on crystal drive current. The step changes in frequency with changes in current strongly suggest that there is nonlinear coupling between the primary mode and other modes. This conclusion is supported by the hysteresis in the $\mathcal{L}$(10 Hz) data from resonator 2 and the data of Table 2, which show that some resonators of this design have lower flicker of frequency noise at 100 °C than at temperature turnover. Figure 8 indicates that the flicker of frequency component of the PM noise can be significantly improved in some resonators by a post-processing bake with the crystal current set to the final operating value (lowest PM noise).

These data raise many questions. What mediates the coupling between the mode of interest and other modes? Is it strain caused by electrode plating, mounting, and/or dislocations and impurities? Can the geometry be altered to optimize the energy trapping and reduce coupling to other modes? What is changing during the high temperature processing? Is it strain or perhaps is it the movement of impurity ions to more stable positions which depend on the drive current? If it is related to impurity ions, would the results be different if swept quartz were used? What is the role of amplitude modulation (AM) noise in the oscillating loop? Does it affect the resulting flicker of frequency noise of the oscillator?

We hope to address some of these questions in the future by comparing the effect of changing electrode size, polishing technique, dislocation density and sweeping on amplitude-frequency effect and flicker of frequency noise.

ACKNOWLEDGMENTS

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10. dBc/Hz refers to dB below the carrier in a 1 Hz bandwidth.