1/f Frequency Noise of 2-GHZ High-Q Thin-Film Sapphire Resonators

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Abstract—**We present experimental results on intrinsic 1/f frequency modulation (FM) noise in high-overtone thin-film sapphire resonators that operate at 2 GHz. The resonators exhibit several high-Q resonant modes approximately 100 kHz apart, which repeat every 13 MHz. A loaded Q of approximately 20000 was estimated from the phase response. The results show that the FM noise of the resonators varied between $S_y(10\text{ Hz}) = -202$ dB relative (rel) to 1/Hz and −210 dB rel to 1/Hz. The equivalent phase modulation (PM) noise of an oscillator using these resonators (assuming a noiseless amplifier) would range from $\mathcal{L}(10\text{ Hz}) = -39$ to −47 dBc/Hz.**

I. Introduction

The frequency stability of an oscillator is a function of the Q of the resonator and the intrinsic noise of its components (resonator, loop amplifier, and gain control circuitry). Thus, important characteristics of a resonator are high Q and low frequency noise. If a resonator with FM noise of $S_y(f)$ is used in an oscillator, its contribution to the PM noise of the oscillator is given by [1]

$$\mathcal{L}(f) = \frac{1}{2}\left(\frac{\nu_o}{f}\right)^2 S_y(f) \qquad (1)$$

where $\mathcal{L}(f)$ is the noise in the oscillator, ν_o is the carrier frequency, and f is the Fourier frequency.

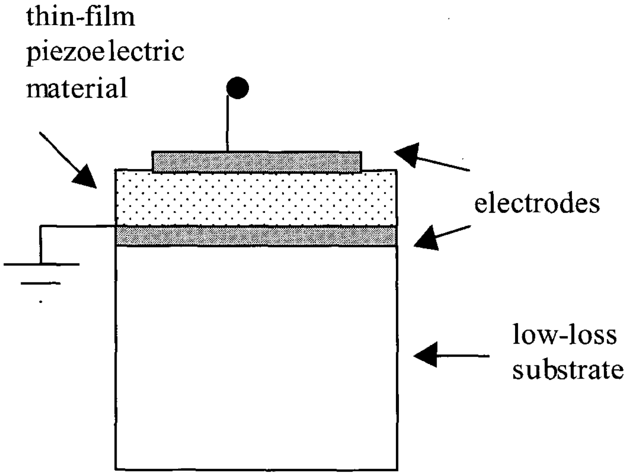

Fig. 1. Diagram of overmoded resonator.

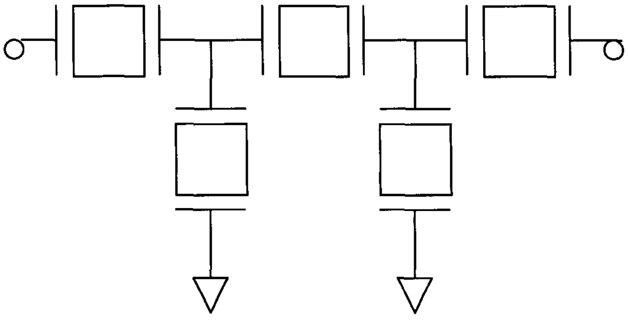

Fig. 2. 3/2 ladder filter structure used (three resonators in series and two resonators in shunt).

In this paper, we report on the intrinsic FM noise of 2-GHz overmoded resonators. These resonators are made of thin-film piezoelectric material deposited on a high-Q sapphire substrate. Fig. 1 shows a diagram of the overmoded resonator. The piezoelectric material was aluminum nitride (2 μm thick). The sapphire used as substrate was 0.5 mm thick, and the aluminum electrodes were 0.2 μm thick. Because the thickness of the substrate is much larger than the thickness of the thin film, the resonator operates at a large mode number. In this study, we used resonators arranged in a 3/2 ladder filter (three resonators in series and two in shunt) as shown in Fig. 2. More details on the resonator design, fabrication, and operation are given in [2], [3]. The overmoded resonators used in this study do not exhibit a turnover temperature, and their temperature coefficient is the temperature coefficient of the sapphire, approximately −30 ppm/°C. The advantages of these resonators over other technologies are their high Q, in addition to their small size, which, in principle, would make possible the building of an oscillator in a very small package.

II. Transmission Characteristics

The resonators were ovenized to stabilize their transmission characteristics. A network analyzer was used to measure the transmission characteristics of the ovenized resonators. The transmission characteristics of the three

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Manuscript received January 11, 2000; accepted June 30, 2000.

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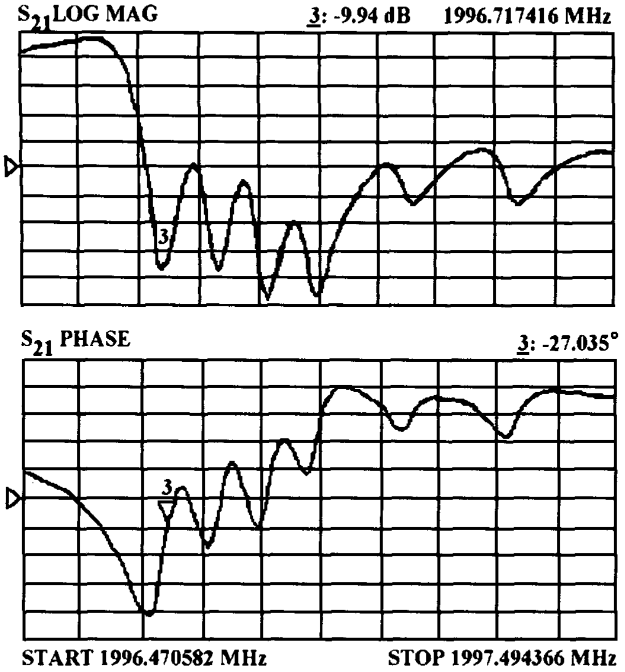

Fig. 3. Transmission characteristics of Resonator 1. The start frequency is 1996.470 582 MHz, and the stop frequency is 1997.494 366 MHz. For the magnitude plot, the reference level is −6.5 dB, and the vertical scale is 1 dB/division. For the phase plot, the reference level is −20°, and the vertical scale is 8.6° per division.

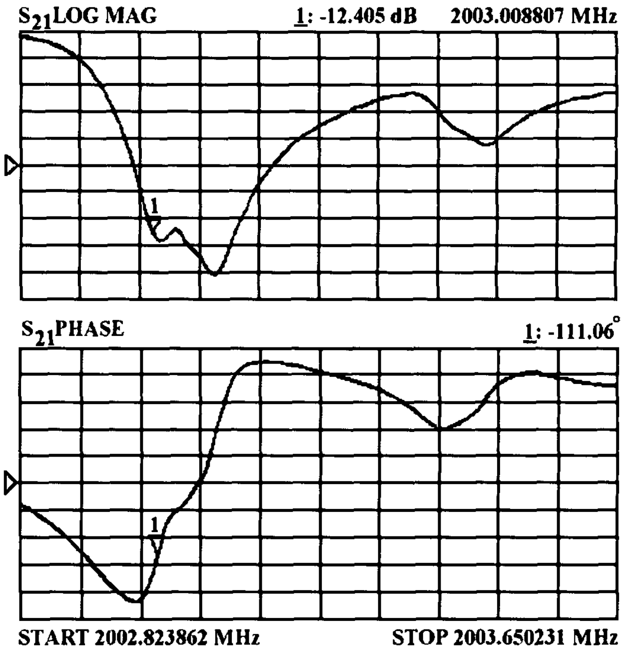

Fig. 4. Transmission characteristics of Resonator 2. The start frequency is 2002.823 862 MHz, and the stop frequency is 2003.650 231 MHz. For the magnitude plot, the reference level is −8.7 dB, and the vertical scale is 1.4 dB/division. For the phase plot, the reference level is −84.4°, and the vertical scale is 9.7° per division.

resonators tested are shown in Fig. 3–5. Resonator 1 shows four high-Q resonances approximately 100 kHz apart, and Resonators 2 and 3 show two high-Q resonances approximately 100 kHz apart. These resonances are repeated approximately every 13 MHz. The insertion loss varies between 10 and 14 dB among the resonators and the different modes. An estimate for the loaded Q of the modes was obtained from the phase response and the relation

$$\Delta\phi = 2Q_L\Delta y \qquad (2)$$

where $\Delta\phi$ refers to the phase difference, Q_L is the loaded Q of the resonator, and Δy refers to the fractional frequency difference. The estimated Q_L was 20000.

III. FREQUENCY NOISE MEASUREMENTS

Fig. 6 shows a simplified block diagram of the frequency discriminator measurement system used for measuring the intrinsic FM noise of the ovenized resonators [4]. A signal generator was used as the driving source, and a single overmoded resonator was used as the frequency discriminator. As shown, carrier suppression was used to improve the noise floor of the measurement system [5], [6].

Fig. 7 shows FM noise results for Resonator 2 at a 12-dBm drive level. In this case, measurements were made at three different modes: $f_1 = 1.990307400$ GHz (Trace A), $f_2 = 2.002994680$ GHz (Trace B), and $f_3 =$

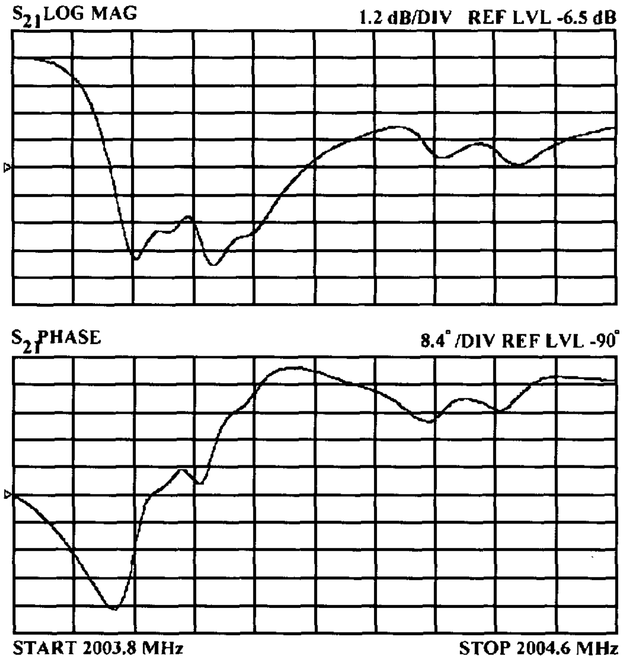

Fig. 5. Transmission characteristics of Resonator 3. The start frequency is 2003.8 MHz, and the stop frequency is 2004.6 MHz. For the magnitude plot, the reference level is −6.5 dB, and the vertical scale is 1.2 dB/division. For the phase plot, the reference level is −90° and the vertical scale is 8.4° per division.

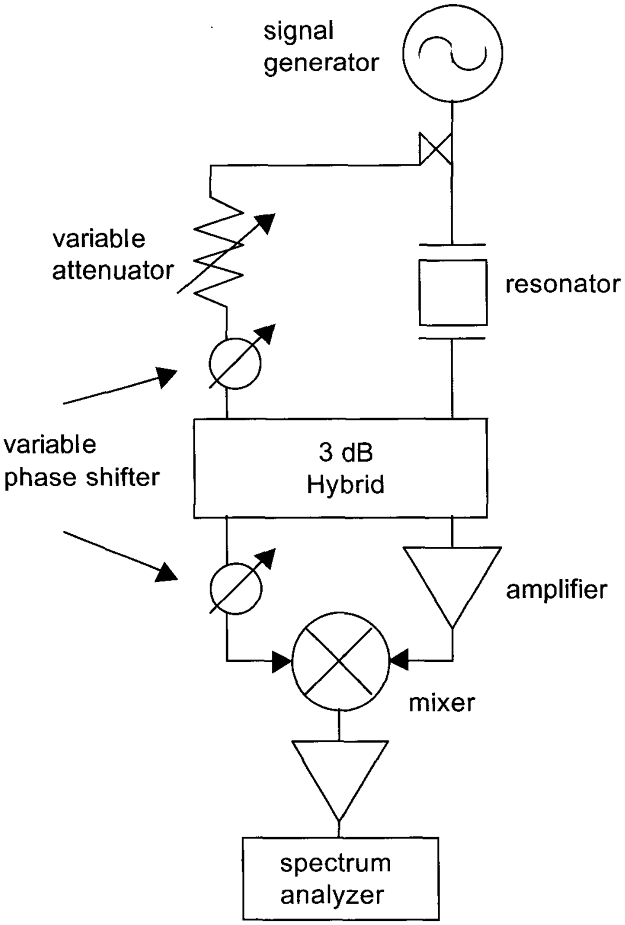

Fig. 6. Block diagram of frequency discriminator measurement system with carrier suppression.

2.003062060 GHz (Trace C). The results for all three modes are very close (within 2 dB). Based on the manufacturer's PM noise specifications, the PM noise of the frequency synthesizer used in the measurement system does not contribute to the measured noise at Fourier frequencies below 1 kHz. Nevertheless, the measured FM noise at Fourier frequencies above 400 Hz was limited by synthesizer noise, probably amplitude modulation (AM) noise.

Fig. 8 shows FM noise results for Resonator 3 at a 12-dBm drive level. In this case, noise measurements were made at two different modes: $f_1 = 2.003935940$ GHz (Trace A) and $f_2 = 2.004041860$ GHz (Trace B). As shown, the two traces are close, within 3 dB.

Table I shows a summary of the FM noise of the three resonators. The column labeled $S_y(10\ \mathrm{Hz})$ refers to the FM noise of the resonators, and the column labeled $\mathcal{L}(10\ \mathrm{Hz})$ refers to the PM noise of an oscillator built using the resonator and a noiseless amplifier. This last column was obtained from the $S_y(f)$ data and (1). These results show that there is a spread of 8 dB in the FM noise of the resonators.

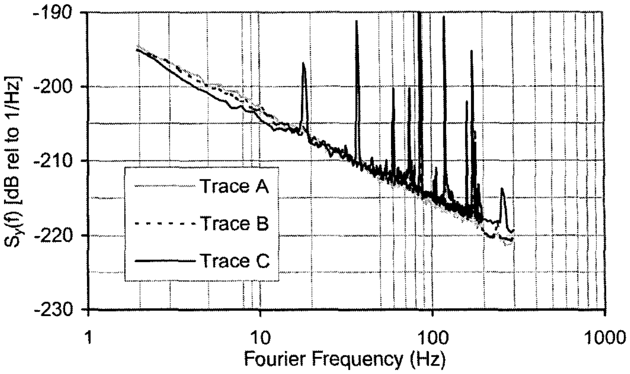

Fig. 7. Intrinsic FM noise in three modes of Resonator 2.

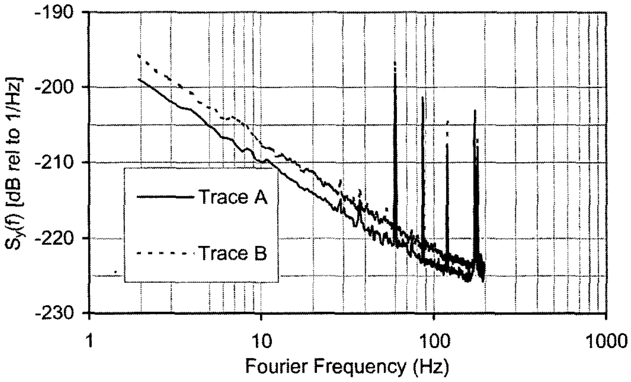

Fig. 8. Intrinsic FM noise in two modes of Resonator 3.

IV. Discussion and Conclusion

The thin-film overmoded resonator transmission characteristics exhibit multiple resonances (100 kHz apart), which repeated every 13 MHz from 1 to 2 GHz. These close resonances are probably due to the lack of parallelism in the surfaces of the substrate. The FM noise of the 2-GHz overmoded resonators was measured using a frequency discriminator measurement system with carrier suppression. To our knowledge, these are the first reported FM noise measurements for this high-Q resonator technology. The spread of the noise results among the three resonators was 8 dB; the noise ranged from $S_y(10\ \mathrm{Hz}) = -202$ dB

TABLE I

Frequency Noise for Overmoded Sapphire Resonators.

Resonator	Frequency (GHz)	$S_y(10\ \mathrm{Hz})$ [dB rel to 1/Hz]	$\mathcal{L}(10\ \mathrm{Hz})$ [dBc/Hz]
1	1.996683000	−202	−39
2	1.990307400	−203	−40
2	2.002994680	−204	−41
2	2.003062060	−204	−41
3	2.003935940	−210	−47
3	2.004041860	−208	−45

rel to 1/Hz to −210 dB rel to 1/Hz. The equivalent PM noise of an oscillator using such resonators (assuming a noiseless amplifier) would range from $\mathcal{L}(10\text{ Hz}) = -39$ to −47 dBc/Hz.

The resulting PM noise is approximately 30 dB lower than the typical PM noise of 2-GHz commercial voltage-controlled oscillator (VCO), approximately $\mathcal{L}(10\text{ Hz}) = -10$ dBc/Hz. However, overmoded resonators lack the tuning capability of the VCOs because of the proximity of the resonant modes. A possible oscillation scheme would be to phase-lock a VCO to the thin-film resonator to obtain lower close-in PM noise and tunability over a 1-GHz range (every 13 MHz). The problem with this scheme is that because of the close proximity of the multiple resonances, a very narrowband filter would be needed to select the correct resonance.

Three other acoustic technologies operate in this general frequency range. Surface transverse wave (STW) resonators have Qs of a few thousand and exhibit low noise; PM noise as low as $\mathcal{L}(10\text{ Hz}) = -50$ dBc/Hz has been reported for 1-GHz STW oscillators [7]. STW resonators can also be used in VCOs, and they exhibit a turnover temperature [8], [9]. Surface acoustic wave (SAW) resonators typically operate at frequencies from 100 MHz to 2 GHz [10]. Phase noise reports of $\mathcal{L}(1\text{ Hz}) = -55$ dBc/Hz for a 500-MHz oscillator with a loaded Q of 1000 has been reported in [11]. This technology can potentially result in low noise oscillators at 2 GHz. In addition, another overmoded resonator previously studied is the high-overtone bulk-acoustic resonator (HBAR) [12]. In these two-port resonators, the high-Q substrate was located between two thin-film piezoelectric transducers. FM noise results of $S_y(100\text{ Hz}) \cong -250$ dB rel to 1/Hz were reported for 640-MHz HBAR resonators [12].

In principle, overmoded resonators can be used to build low-noise oscillators that are very small in size, but the circuit would require a pre-selector to select the oscillation mode. These overmoded resonators are potentially much smaller than other competing resonator technologies; nevertheless, these overmoded resonators do not have a turnover temperature and exhibit a temperature coefficient of approximately −30 ppm/°C.

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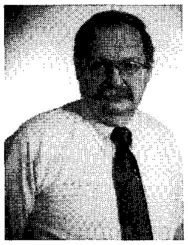
He received the 1995 European "Time and Frequency" Award from the Societe Francaise des Microtechniques et de Chromometrie "for outstanding work in ion storage physics, design and development of passive hydrogen masers, measurements of phase noise in passive resonators, very low noise electronics and phase noise metrology." He is the recipient of the 1995 IEEE Rabi Award for "major contributions to the characterization of noise and other instabilities of local oscillators and their effects on atomic frequency standards," the 1999 Edward Bennett Rosa Award "for leadership in development and transfer to industry of state-of-the-art standards and methods for measuring spectral purity in electronic systems", and the IEEE Third Millennium Medal. He has also received three silver medals from the US Department of Commerce for fundamental advances in high resolution spectroscopy and frequency standards, the development of passive hydrogen masers, and the development and application of state-of-the-art standards and methods for spectral purity measurements in electronic systems. Dr. Walls is a fellow of the American Physical Society, a Senior Member of the IEEE, a member of the Technical Program Committee of the IEEE Frequency Control Symposium, and also a member of the Scientific Committee of the European Time and Frequency Forum.



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