Spurious Suppression Technique for Edge-Trap-Type SAW Resonators and Their Application to 1-GHz Wide-Band SAW-VCOs for Mobile Communications

Tsuyoshi Kachi, Atsushi Isobe, Atsushi Sumioka†, Kengo Asai and Mitsutaka Hikita
Central Research Laboratory, Hitachi Ltd. Higashi-Koigakubo 1-230, Kokubunji, Tokyo, Japan
†Hitachi Kokusai Electric Inc., Miyuki-Cho 32, Kodaira-Shi, Tokyo, Japan

Abstract— **1-GHz wide-band VCOs using SAW resonators have been successfully developed. A control-voltage sensitivity of over 5%/V has been achieved by using new edge-trap-type SAW-resonators. Optimizing the reflectors of SAW resonators is very effective for suppressing the spurious resonance of the Rayleigh wave in the oscillation band.**

Two types of VCOs are compared. One uses a Si bipolar junction transistor as a feedback amplifier and the other uses a GaAs MESFET. Both VCOs achieved a control-voltage sensitivity of over 5%/V and a phase noise of less than -107 dBc/Hz at a 25 kHz offset frequency from the carrier frequency. The GaAs MESFET VCO showed better phase noise performance than the Si transistor VCO at a 30-kHz or greater offset frequency. By changing the amplifier elements, it is possible to achieve the requirements for both local VCOs and transmission VCOs for wireless communication terminals.

I. Introduction

Surface acoustic wave (SAW) resonators have been considered to be attractive as voltage-controlled oscillators (VCOs) due to their compactness and high Q value. However, it has also been considered difficult to achieve wide-band SAW-VCOs, since the bandwidth of SAW resonators has been smaller than that of other resonators (micro-strip-line resonators, dielectric resonators, etc.).

Recently, edge-trap-type SAW (also known as "grating-mode-type SAW") resonators that show large k^2 have been developed [3]. Wide-band VCOs for 170-MHz-band, 400-MHz-band [1], and 1-GHz-band [2] application have been developed by using edge-trap-type SAW resonators.

We have investigated the phase noise performance of VCOs using edge-trap-type SAW resonators. In particular, we have focused on spurious resonances in the VCO oscillation band. In this paper, we describe a problem with previous edge-trap-type SAW resonators and present a solution to this problem. The difference in phase-noise performance by using different transistors in VCOs is also discussed.

II. Edge-Trap-Type SAW Resonator

A. Impedance ripple in oscillation band

Edge-trap-type SAW resonators have thick (typically over 10% of the SAW wavelength) Al electrodes fabricated on 15 ˚ -rotated Y-cut X-propagation lithium niobate (15 ˚ YX-LN) substrates. These resonators provide a large k^2 of up to 23% and a high Q value of over 210 at the resonant frequency.

In a previous work [2], our group introduced the diamond-shaped inter-digital transducer (IDT) structure. Figure 1 is a top view of a typical diamond-shaped, one-port SAW resonator. The aperture length decreases on either side of the IDT to minimize the resistance of the electrodes and the chip size. Fig. 2 shows a close-up view of the IDT. To reduce leakage of excited SAWs, reflectors are placed between the busbars and the crossing area.

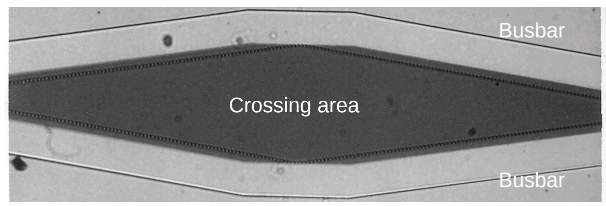

Fig. 1. Top view of diamond-shaped SAW resonator.

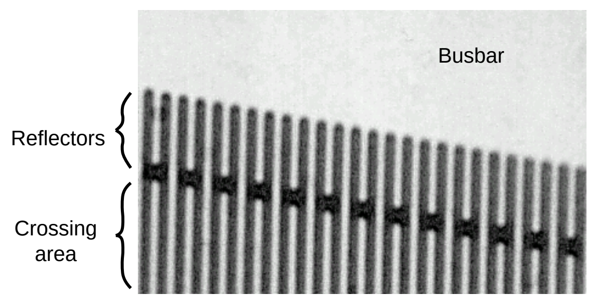

Fig. 2. Close-up view of IDT (reflectors and crossing area are shown).

Fig. 3 shows the impedance response (real part only) of a 200-MHz-band SAW resonator using the diamond-shaped IDT structure. A small ripple (A), which has not been seen for conventional IDTs, appeared at a lower frequency than the resonant frequency (f_r) (B). Accounting for this ripple is essential for SAW-VCO performance, since the VCO oscillation range includes this frequency.

We have fabricated various SAW resonators with different f_r values (i.e., different electrode periods and Al thicknesses), and we have found that all of them had ripples at a frequency corresponding to the same SAW velocity of about 3160 m/s. Therefore, we have concluded that this phenomenon is not due to fabrication process variation but is an inherent problem of SAW resonators using the diamond-shaped IDT structure.

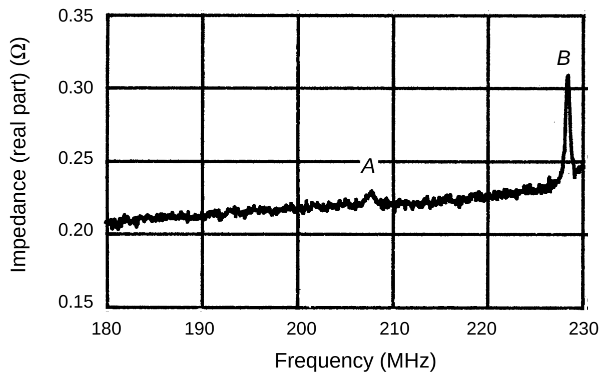

Fig. 3. Impedance response of 200-MHz-band SAW resonator.

B. Simulation and Analysis

To analyze this phenomenon, we have simulated the impedance response of an infinite IDT. The simulator was programmed by combining a finite-element method and an analytical method [3]. The calculated impedance responses are shown in Figs. 4 and 5. When the SAW propagation direction was exactly parallel to the crystal's principal axis (x-axis. i.e., $\phi = 0$), no ripple was found (Fig. 4). However, for $\phi = 2.5^\circ$, a ripple appeared at 3166 m/s (Fig. 5).

We think that the origin of this ripple is a spurious resonance of the Rayleigh wave. The Rayleigh wave acts as a spurious mode for edge-trap SAWs. Reducing the spurious resonance of the Rayleigh wave requires setting the Al grating thickness–wavelength ratio (h/λ_0) to around 0.125 [1]. This condition is sufficient when the SAW propagation direction is parallel to the x-axis of the substrate crystal; however, when the direction slightly differs from the x-axis, the spurious suppression effect is overcome by the asymmetry of the SAW velocity [4]. As a result, spurious resonances of the Rayleigh wave are observed.

Based on the simulation results, we have concluded that the mechanism of the ripple is as follows. Fig. 6 shows the layout of a diamond-shaped IDT in the region close to a busbar. From the tip of an electrode finger, SAWs are excited in all directions. Among the excited SAWs, some that propagate in a slightly different direction from the x-axis cause standing waves if the electrode fingers of the reflectors are arranged in the same phase as the grating area. This situation is nearly the same as the simulation conditions for the spurious resonance shown in Fig. 5.

C. Spurious Suppression Technique

To suppress the spurious resonance caused by the reflectors, we have designed a new IDT layout, shown in Fig. 7.

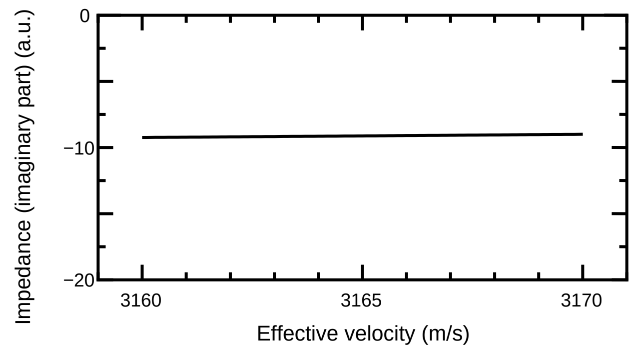

Fig. 4. Calculated impedance response of infinite IDT ($\phi = 0^\circ$).

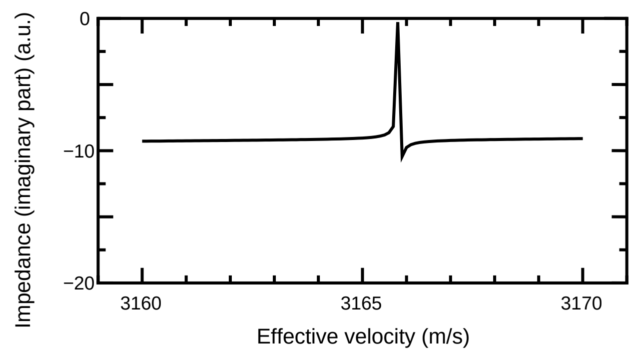

Fig. 5. Calculated impedance response of infinite IDT ($\phi = 2.5^\circ$).

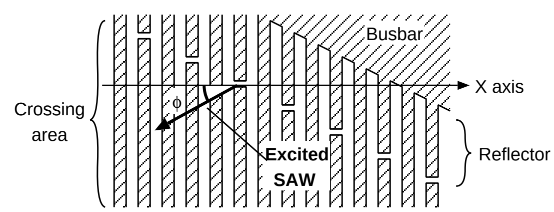

Fig. 6. Mechanism of ripple appearance.

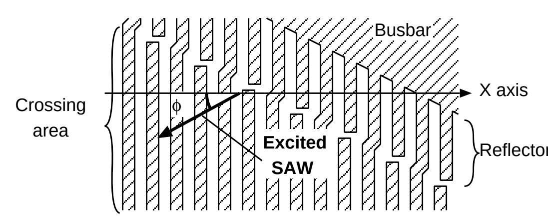

Fig. 7. New layout to suppress ripple appearance.

In this layout, the reflectors are shifted along the x-axis, so stray SAWs do not cause standing waves.

We have fabricated a 200-MHz-band SAW resonator using this layout and confirmed that the ripple disappeared, as shown in Fig. 8.

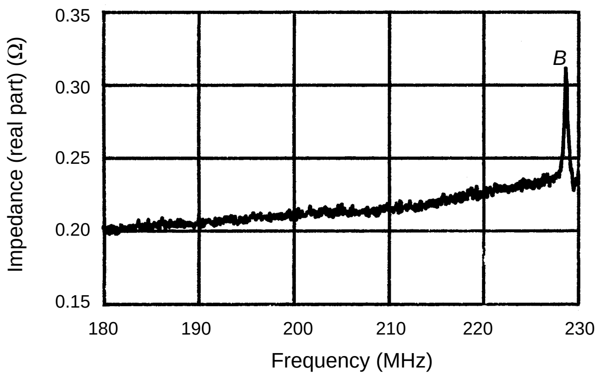

Fig. 8. Impedance response of 200-MHz-band SAW resonator with shifted reflector layout.

We have also fabricated 1-GHz-band SAW resonators for VCOs. Figure 9 shows the impedance response of a 1-GHz-band, diamond-shaped, one-port SAW resonator that uses the spurious suppression technique. This resonator has 400-nm-thick Al electrodes paired on a 15˚YX-$LiNbO_3$ substrate. The measured impedance includes about 1 nH of parasitic inductance from the bonding wires. Single-resonant response was observed between 900 MHz and 1.1 GHz. The Q value at f_r was about 210, and there was no spurious resonance below f_r.

III. Wide-Band Low-Noise SAW-VCO

A. VCO Circuits

We have fabricated two types of feedback amplifier since this device is as important as the resonator in determining VCO noise performance. One consisted of a Si bipolar junction transistor (Si-BJT), and the other was a GaAs metal-silicon field-effect transistor (GaAs-MESFET). The electrical circuits for these VCOs are shown in Figs. 10 and 11. The Colpitts-type oscillation circuits consisted of a SAW resonator, external inductor, variable-capacitor diode, feedback capacitor, buffer amplifier, and other components. They were all integrated on glass-epoxy substrates.

B. Oscillation Frequency and Bandwidth

It was necessary to optimize the constants of the feedback capacitors, the extension inductance, and many other components of each circuit individually, since the input impedances of the two transistors are completely different.

Fig. 12 shows the oscillation frequencies of the SAW-

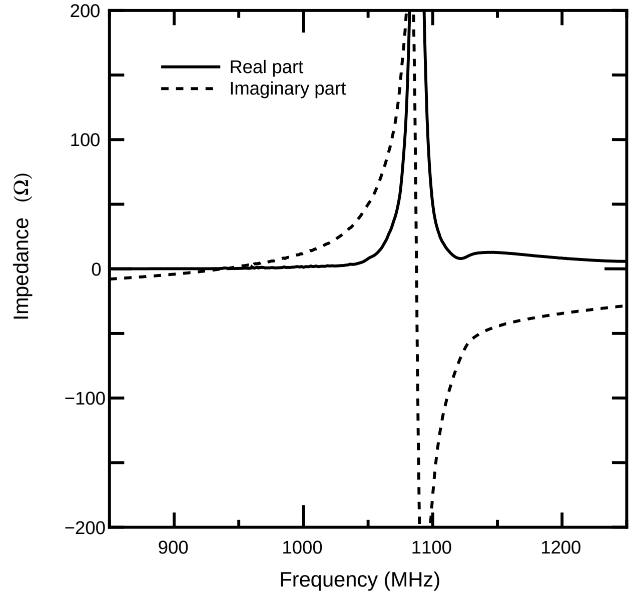

Fig. 9. Impedance response of 1-GHz-band, diamond-shaped SAW resonator.

VCOs. Both the oscillation frequency and the control-voltage sensitivity were adjusted to be almost equal. We achieved high control-voltage sensitivities of 6.9 %/V for the SAW-VCO with the Si-BJT and 5.0 %/V for the one with the GaAs-MESFET.

C. Phase Noise Performance

The phase noise dependence on offset frequency (f_{off}) is shown in Fig. 13. The phase noise at f_{off}=25 kHz was -110 dBc/Hz for the Si-BJT VCO and -107 dBc/Hz

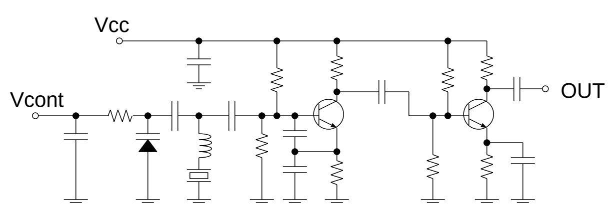

Fig. 10. VCO circuit with Si bipolar transistor.

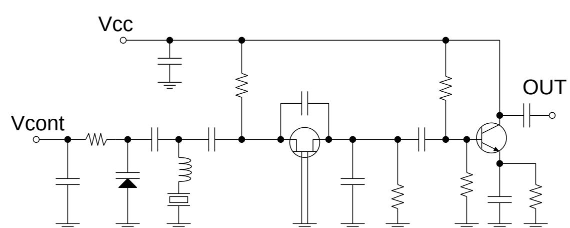

Fig. 11. VCO circuit with GaAs MESFET.

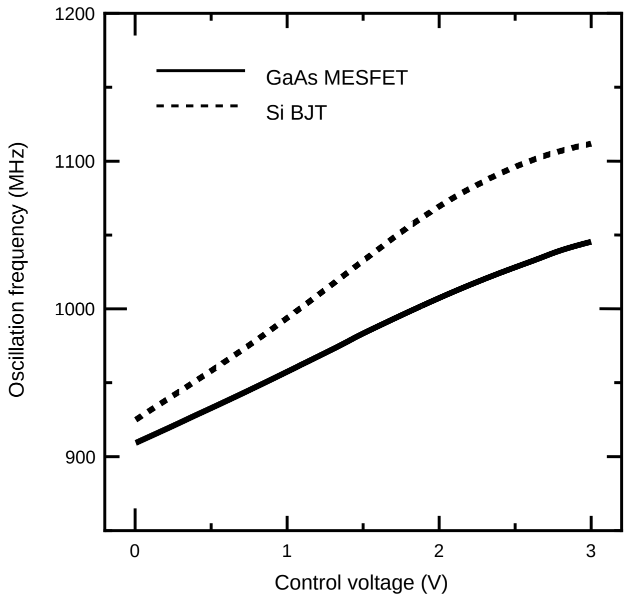

Fig. 12. Oscillation frequency vs. control voltage.

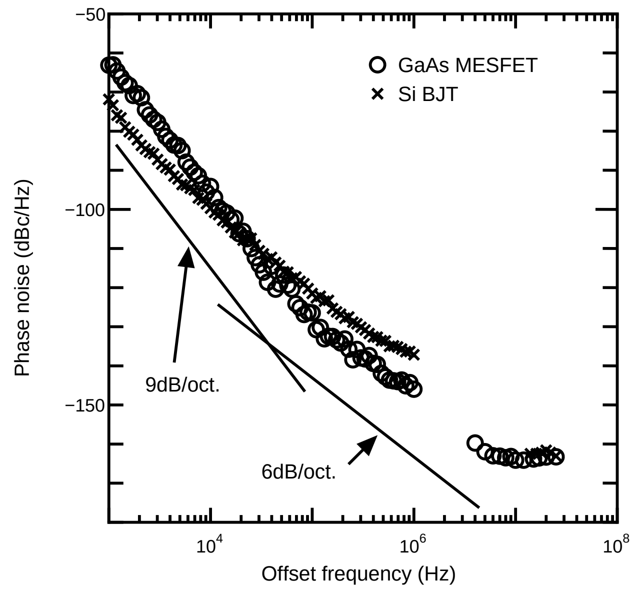

Fig. 13. Phase noise characteristics of 1-GHz-band SAW-VCOs.

for the GaAs-MESFET VCO. Near the carrier frequency, the Si-BJT VCO showed lower phase noise than the GaAs-MESFET VCO. At frequencies 30 kHz or more away from the carrier frequency, however, this relationship was reversed.

These characteristics can be explained by the difference in the noise characteristics of the transistors. The phase-noise slope for the GaAs-MESFET VCO near the carrier frequency was 9 dB/octave. This 9-dB/octave slope derives from the up-converted 1/f noise at low frequency. Therefore, this property originates from the fact that the low-frequency noise (1/f noise) of the GaAS-MESFETs is larger than that of the Si-BJTs.

By comparison, at a frequency 100 kHz away from the carrier frequency, both the Si-BJT and GaAs-MESFET VCOs had 6-dB/octave slopes and the Si-BJT VCO had lower phase-noise. Since the 6-dB/octave noise is determined by the flat noise at low frequency, this result agree with the fact that GaAs-MESFETs have smaller noise-figure (NF) than Si-BJTs.

IV. Conclusion

We have found a spurious resonance of the Rayleigh wave in diamond-shaped, edge-trap-type SAW resonators. This phenomenon has not been observed in conventional IDT layouts but is inherent to diamond-shaped IDTs. Optimizing the reflector arrangement is very effective for suppressing this spurious resonance. We have fabricated 200-MHz-band SAW resonators using this technique and confirmed its effectiveness.

We have also fabricated SAW-VCOs using 1-GHz-band SAW resonators. We compared feedback amplifiers based on Si-BJTs and GaAs-MESFETs. The SAW-VCO with the Si-BJT showed better phase noise performance than the one with the GaAs-MESFET at frequencies near the carrier frequency, but the situation was reversed at the frequencies more than 30kHz away from the carrier frequency.

These results suggest that we must select transistors for VCOs more carefully. For example, a Si-BJT VCO is suitable as a local-VCO (Lo-VCO) in cellular radio systems, since a Lo-VCO requires high phase noise performance near the carrier frequency. On the other hand, a GaAs-MESFET VCO has advantages as a transmitter VCO (Tx-VCO), which requires low-noise properties at frequencies away from the carrier frequency.

References

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