Study on Generation Mechanisms of Third-order Nonlinear Signals in SAW Devices on the Basis of Simulation

1. Introduction

Recently, linearity improvement is one of the most important subjects in the research and development of SAW and BAW devices. In this situation, better understanding of the generation mechanisms of nonlinear signals are crucial.

In this work, we discuss the generation mechanisms of third-order nonlinearity in SAW devices. For this discussion, simulation method of nonlinear signals, in which conceivable all generation mechanisms of nonlinearity are taken into account, is proposed. As the result of comparisons of simulation results and measured data, it is shown that contributions of each mechanism to nonlinear signals change markedly with the input and output frequency conditions.

2. Simulation Method of Nonlinear Signals

First, an analysis model used in this method is shown in Fig. 1. This model has multiple sources as shown in Fig. 2.

By introducing nonlinear terms into the piezoelectric constructive equation, nonlinear stress $T_N$ and nonlinear current $I_N$ generated by third-order nonlinearrity at each receiving point $l$ in the case of simultaneous two signals input are expressed as forrows:

$$T_{N_{l_1, l_2}} = \frac{1}{\varepsilon_1 \varepsilon_0} \left[ \mu_{m_{l_1, l_2}}^{(30)} I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) \right. $$

$$+ \mu_{m_{l_1, l_2}}^{(31)} \left[ 2 I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right]$$

$$+ \mu_{m_{l_1, l_2}}^{(32)} \left[ 2 I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right]$$

$$+ \mu_{m_{l_1, l_2}}^{(33)} \left[ I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right]$$

$$\left. + \mu_{m_{l_1, l_2}}^{(34)} \left[ I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right] \right]$$

$$I_{N_{l_1, l_2}} = \frac{2 \omega_1 + \omega_2}{\varepsilon_1 \varepsilon_0} \mu_{m_{l_1, l_2}}^{(30)} \left[ I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) \right. $$

$$+ \mu_{m_{l_1, l_2}}^{(31)} \left[ 2 I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right]$$

$$+ \mu_{m_{l_1, l_2}}^{(32)} \left[ 2 I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right]$$

$$+ \mu_{m_{l_1, l_2}}^{(33)} \left[ I_{m_{l_1, l_2}}^{(A)} (\omega_1) i I_{m_{l_1, l_2}}^{(A)} (\omega_2) + \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_1) i \hat{I}_{m_{l_1, l_2}}^{(A)} (\omega_2) \right]$$

where, $\omega_1$ and $\omega_2$ are angular frequencies of input signals, and $\mu_{m_{l_1, l_2}}^{(30)}$ and $\mu_{m_{l_1, l_2}}^{(31)}$ are nonlinear coefficients. In particular, $\mu_{m_{l_1, l_2}}^{(30)}$ and $\mu_{m_{l_1, l_2}}^{(31)}$ represent the nonlinear elasticity and dielectrics, respectively, while the others represent the nonlinearity of electromechanical coupling. In addition, $I_{m_{l_1, l_2}}^{(A)}$ and $I_{m_{l_1, l_2}}^{(E)}$ are linear currents at acoustic and electric pass, respectively, and they can be derived from linear case analysis such as coupling of modes theory. Therefore, provided that the nonlinear coefficients $\mu_{m_{l_1, l_2}}^{(30)}$ and $\mu_{m_{l_1, l_2}}^{(31)}$ are determined a priori, the nonlinear stress and the nonlinear current can be calculated by using only the results of a conventional linear analysis.

Nonlinear signal levels at external terminals of a target device are estimated by giving obtained nonlinear stresses and nonlinear currents into an equivalent circuit of it as the voltage and current sources as shown in Fig. 2.

Fig. 1 Analysis Model.

Fig. 2 Estimation of Nonlinear Signal Level.
3. Simulation and discussion

Fig. 3 shows experimental and fitted simulation data of third-order harmonics (H3) and intermodulation distortion (IMD3) $2f_1-f_2$ of a one-port SAW resonator. Resonance frequency $f_r$ and anti-resonance frequency $f_a$ of the fabricated resonator are 835 and 863 MHz, respectively. In the measurement of H3, input frequency was swept from 800 to 900 MHz, and output signal appeared at 2.4 to 2.7 GHz was detected. On the other hand, in the measurement of IMD3, two input signals with frequencies $f_1$ and $f_2$ were applied simultaneously. Frequency $f_1$ was swept from 824 to 849 MHz, while $f_2$ was swept to be $f_1-45$ MHz. Then, output signal $2f_1-f_2$ appeared at 869 to 894 MHz was detected. In these measurements, powers of input signals at the input terminal were set at 15 dBm. In Fig. 3, simulated data agree well with measured data. For all calculations, identical nonlinear coefficients were used. This indicates validity of the proposed model.

Fig. 4 shows the contributions of each nonlinear term to the simulation results given in Fig. 3. For the case of H3 in Fig. 4(a), effects of $\mu_e^{(03)}$, $\mu_e^{(21)}$, and $\mu_e^{(30)}$ are dominant. In this case, since input signal $f_1$ is close to $f_r$, the effect of the coefficient $\mu_e^{(03)}$ representing acoustic nonlinearity is significant. On the other hand, in the case of IMD3 in Fig. 4(b), the characteristics is mostly governed by the effect of $\mu_m^{(03)}$. This is because all of two input signals and output signals are close to $f_r$ and thus acoustic waves are excited and detected efficiently for both the linear and nonlinear signals.

As shown in Fig. 4, significances of each nonlinear term to the nonlinear responses are change markedly depending on the driving conditions. In this case, it was shown that influences of $I_N$ is dominant for the out-band nonlinear signal output while $T_N$ is significant when a nonlinear signal is generated close to $f_r$.

4. Conclusion

In this work, generation mechanisms of third-order nonlinearity are discussed by using the simulation method proposed for this discussion. The simulation results showed very good agreement with measured data when the nonlinear coefficients were properly determined. In addition, it was shown that the significances of each nonlinear coefficient are change markedly depending on the driving condition.

References