Optimization of frequency characteristics for SAW device using apodization weighting method*

ZHOU Lei (周磊)[1,2], ZHANG Kai-liang (张楷亮)[1], WANG Fang (王芳)[1], HAN Ye-mei (韩叶梅)[1], MIAO Yin-ping (苗银萍)[1], LI Dong-mei (李冬梅)[2], and LIANG Sheng-fa (梁圣法)[2]**

1. Tianjin Key Laboratory of Film Electronic & Communication Devices, School of Electronics Information Engineering, Tianjin University of Technology, Tianjin 300384, China

2. Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China

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In this paper, the positive influence of apodization weighting method on frequency characteristics of surface acoustic wave (SAW) temperature sensor is investigated. Simulation and experiment results show that side lobe suppression abilities of the sensor can be improved by using apodization weighting which is based on Chebyshev window. Meanwhile, we find that the side lobe of the sensor can be further restrained, when the dummy electrodes are removed. Frequency-temperature characteristics of the devices are independent of the inclusion of dummy electrodes. The apodization weighted SAW temperature sensor shows great application potential in occasions with strong electromagnetic interference.

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Surface acoustic wave (SAW) devices play an indispensable role in the Internet of things era as a significant channel for information transmission and processing[1-4]. Conventional temperature sensors cannot be used in special occasions, such as enclosed space, rotational motion and other similar cases[5]. Compared with the conventional temperature sensors, SAW temperature sensor can capture temperature information accurately via wireless and passive sensing mode[6]. Nonetheless, the existing ordinary SAW temperature sensors have identical finger length which can be regarded as rectangular window weighted. Due to the identical finger length, these ordinary sensors exhibit weak ability for side lobe suppression, which greatly weakens the sensitivity and resolution of the sensors[7].

The side lobes of frequency response can be effectively suppressed by employing weighting technique which was first applied to the SAW filter to optimize the design of SAW sensor[6]. Due to the fact that the intensity of the excited SAW is proportional to overlap length of adjacent interdigital transducer (IDT) fingers, the frequency response of apodization weighted devices can be accurately controlled by employing various window functions to adjust the overlap length. The spatial mapping of time domain information into an electrode pattern is called apodization weighting[8]. Therefore, the apodization weighting method is most frequently used among all weighted methods. So far, there are several window functions can be applied to weighting functions, such as Hamming window and Chebyshev window.

In this paper, the apodization weighting method is analyzed and simulated. Then, one-port resonator type SAW temperature sensors with different IDT structures are fabricated, and the frequency characteristics are tested, which are consistent with the simulation results. Furthermore, the effects of dummy electrodes on frequency characteristics of weighted sensors are revealed. Finally, temperature-frequency characteristics of the optimized SAW temperature sensor are analyzed.

In this paper, the center frequency of the designed sensor is set to be 433 MHz, and the SAW wavelength (λ) is 10.72 μm. The sensors consist of one-port resonators with 200 electrode pairs in the IDT, and 200 electrode short-circuited grating reflectors are placed in either side of the IDT with electrodes width of λ/4 and mark to space ratio of 1:1. Both the aperture of non-apodized IDT and the maximum aperture of apodized IDT are 100λ.

As shown in Fig.1, the SAW resonator sensors are fabricated by employing lift-off techniques to pattern a 100 nm-thick aluminum thin film which is deposited on 64° YX $LiNbO_3$ wafer. The mask used in the photolithography process is made in aid of Matlab software.

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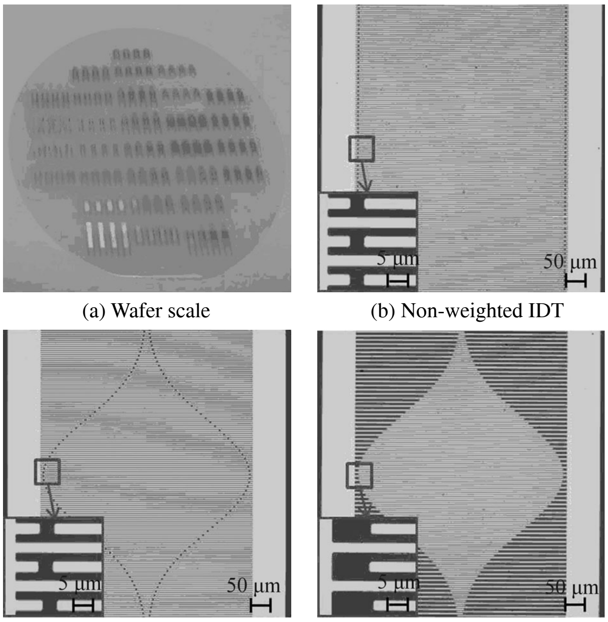
** E-mail: kailiang_zhang@163.com



(a) Wafer scale (b) Non-weighted IDT

(c) Chebyshev window weighted IDT with dummy electrodes (d) Chebyshev window weighted IDT without dummy electrodes

Fig.1 Different view angles of the manufactured devices

Apodization weighting method is dependent on the window functions. Different window functions exhibit diverse weighting effects[9]. In this paper, various window functions weighted IDT are simulated by Matlab software as shown in Fig.2. Compared with rectangular window which can be seen as non-weighted IDT, Chebyshev window can cause the lower side lobe level which suggests the stronger side lobe rejection. In addition, Chebyshev window weighted signal has the same side lobes heights which can be observed in detailed drawing.

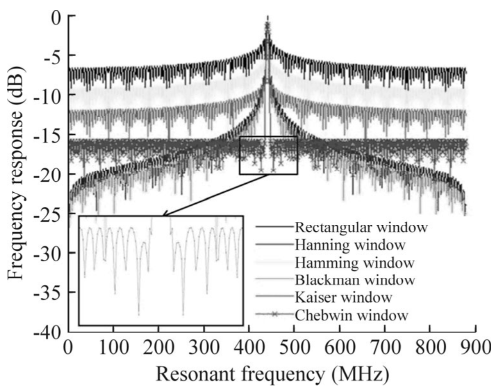


Fig.2 Frequency responses of weighted IDT with various window functions

Based on the above-mentioned simulation, various SAW temperature sensors are designed and fabricated. Tab.1 shows the side lobe level of apodization weighted SAW devices with dummy electrodes. All of the devices have the almost identical parameters, and the difference only lies in the type of window functions for apodization weighting.

As seen from Tab.1, SAW resonators weighted by rectangular window show the weakest side lobe rejection performance among the listed devices, while Chebyshev window weighted SAW resonators have the best results, which performs the side lobe level for up to –16.12 dB. The use of the window functions based apodization weighting method results in the reduction of side lobe level for devices of the same type, which agrees with the simulation. Both results confirm that apodization weighting can effectively suppress the side lobes, and Chebyshev window weighted SAW resonators have the lowest side lobe level. The mechanism of apodization weighting and the Chebyshev window are discussed as follows.

Tab.1 Side lobe levels of diverse window functions

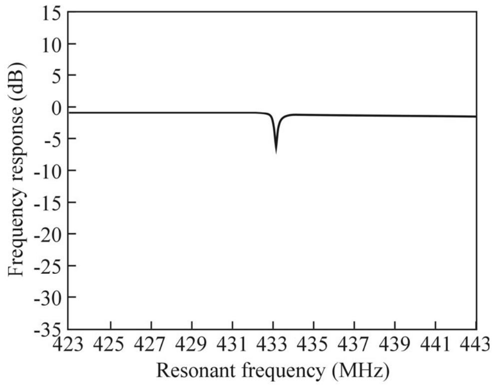
No.	Window function type	Side lobe level (dB)
1	Rectangular window	–5.21
2	Hamming window	–8.77
3	Kaiser window	–11.85
4	Hanning window	–12.68
5	Blackman window	–13.23
6	Chebyshev window	–16.12

For SAW devices, the impulse response is provided by the inverse Fourier transform of the frequency response. Therefore, the impulse response $h(t)$ corresponding frequency response $H(\omega S_{\mathrm{s}})$ is given by

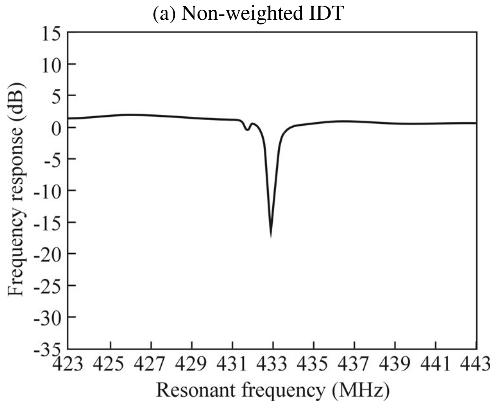
$$h(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}H(\omega S_{\mathrm{s}})\mathrm{e}^{\mathrm{j}\omega t}\mathrm{d}\omega=\sum_{n=-N}^{N}A_n\delta(t-n\tau)\ , \tag{1}$$

where $\delta(t)$ is the delta function, and τ is the SAW propagation delay time in a pair of IDT electrodes[10]. As shown in Eq.(1), the weighting of the IDT corresponds to the waveform of the impulse response. The Fourier transform of the apodization weighting function corresponds to the frequency response of SAW devices. It reveals that the appearance of side lobes in the frequency response characteristic is caused by a nonzero gradient in the weighting function. The high side lobe level appearing in non-apodized IDT which can be seen as rectangular weighted IDT is mainly due to the large discontinuity at the IDT ends. Hence, the side lobes can be effectively suppressed by using smooth weighting function.

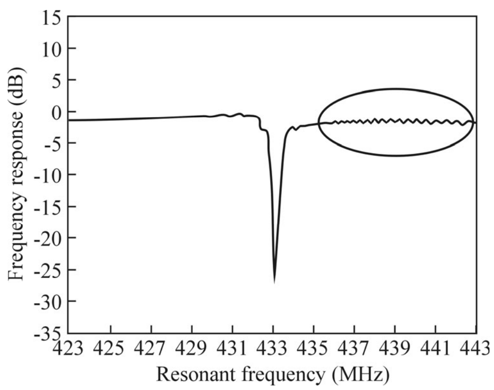
As exhibited in Fig.3, the side lobe level of non-weighted SAW resonators is higher than that of weighted SAW resonators which are consistent with the simulation results. Above all, for Chebyshev window weighted SAW resonators, the resonators without dummy electrodes have much lower side lobe level than that of the resonators with dummy electrodes, while the side lobes of the former exhibits obvious jitter which is shown inside the ellipse in Fig.3(c).



(a) Non-weighted IDT



(b) Chebyshev window weighted IDT with dummy electrodes



(c) Chebyshev window weighted IDT without dummy electrodes

Fig.3 Frequency characteristics of different SAW resonators

In traditional theory, the dummy electrodes are added to maintain the unified phase velocity constant across the aperture[11]. The electrical properties of dummy electrodes have no effect on SAW generation and transmission, because adjacent electrodes are of the same polarity and voltage. However, when the SAW passes the surface area of piezoelectric substrate which is covered with dummy electrodes, the additional energy is consumed due to the mass loading of dummy electrodes, and the side lobe level is raised. Therefore, when the uniform wavefront is partly sacrificed, the low side lobe level is gained.

Fig.4 shows resonant frequency versus temperature for the SAW sensor employing Chebyshev window weighted IDTs with and without dummy electrodes. The line is a fitting straight-line of the measured resonant frequency values for the weighted IDT without dummy electrodes. The resonance frequencies of both sensors decline with the increase of temperature, and the whole process is approximately in linearity. The sensitivity of the sensor without dummy electrodes is about –27.940 1 kHz/°C. Note that both weighted sensors have similar frequency-temperature characteristics. It seems that dummy electrodes have little effect on frequency-temperature characteristic of SAW sensor.

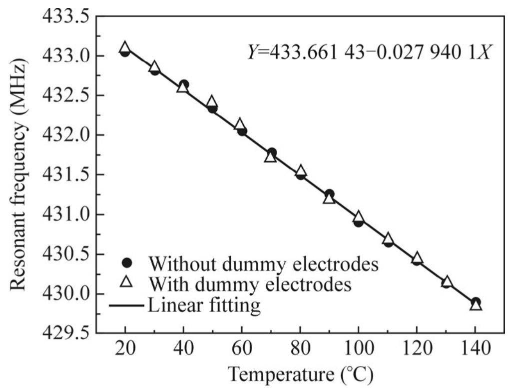


Fig.4 Resonant frequency versus temperature for SAW sensors employing Chebyshev window weighted IDTs with and without dummy electrodes

In this paper, an SAW temperature sensor is designed and fabricated which is composed of the Chebyshev window weighted resonators without dummy electrodes and the short-circuited grating reflectors. Frequency response characteristics of the SAW temperature sensors are optimized by employing apodization weighting method. Both the simulation results and the experimental results show that the side lobe suppression ability of the sensors can be improved, and the device with Chebyshev window exhibits the lowest side lobe level and the highest sensitivity. In addition, dummy electrodes are removed to further enhance the frequency response of apodization weighted SAW sensors. The designed temperature sensor can be applied in the complex electromagnetic environment to meet the application requirements in high sensitivity.

References

[1] F. Pan, Surface Acoustic Wave Materials and Devices, Beijing: Science Press, 2012.

[2] Liu Xiao-chen, Li Kun, Xuan Xiu-wei, Cao Yang and Teng Jian-fu, Optoelectronics Letters **10**, 340 (2014).

[3] Zhu Yu-qing, Chen Xi-Ming, Li Fu-long, Li Xiao-wei and Yang Bao-he, Journal of Optoelectronics·Laser **24**, 1739 (2013). (in Chinese)

[4] Zhang Qian, Chen Xi-ming, Yang Bao-he, Ying Ju-qian and Wu Xiao-guo, Journal of Optoelectronics·Laser **24**, 935 (2013). (in Chinese)

[5] Along Kang, Chenrui Zhang, Xiaojun Ji, Tao Han, Ruisheng Li and Xianwei Li, Sensors and Actuators A: Physical **201**, 105 (2013).

[6] B. François, S. Sakharov, C. Droit, Z. Davis, D. Richter, H. Fritze, G. Martin, J. M. Friedt, V. P. Plessky, G. Brückner, E. Mayer, L. Reindl, T. Karachalios, W. Schiffers, C. Roux and S. Ballandras, Procedia Engineering **47**, 1227 (2012).

[7] Reindl L. M. and Shrena I. M., IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control **51**, 1457 (2004).

[8] Peng Z., Greve D. W., Oppenheim I. J., Tao-Lun Chin and Malone V., IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control **59**, 295 (2012).

[9] Malocha D. C., Evolution of the SAW Transducer for Communication Systems, IEEE Symposium on Ultrasonics **1**, 302 (2004).

[10] Vigil A. J., Abbott B. P. and Malocha D. C., A Study of the Effects of Apodized Structure Geometries on SAW Filter Parameters, IEEE Symposium on Ultrasonics, 139 (1987).

[11] Holland M. G. and Claiborne L. T., Proceedings of the IEEE **62**, 582 (1974).