SAW Dual Channel Current Sensor with FeNi Film

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Abstract. The designs of two-channel passive wireless SAW current sensors with a sensitive element in the form of a FeNi film, as well as with a magnetically sensitive external impedance, are proposed and considered. Such sensors have high sensitivity and therefore they can be installed not in the gap of the magnetic circuit, located around the conductive bus, but directly on it.

Keywords: SAW current sensor · FeNi film · Inter-digital transducer · S11 parameter · External impedance

1 Introduction

The magnetic field of surface acoustic waves (SAWs) sensors on the basis of changes of inductance in the magnetic gap, located around the current bar, and also on the basis of changes in the capacitance of varactors under the tension, induced in the coil wound on this magnetic core were described in [1]. Such sensors must necessarily have a magnetic circuit for their operation, which significantly increases the weight and dimensions of the sensor, as well as complicates its installation.

At the same time, similar sensors are possible; under influence of the magnetic field around the conductive bus, the SAWs speed changes sufficiently in them to detect the current in the bus at currents in units of amperes. This became possible due to the magnetically sensitive films, deposited on the surface of the substrate; SAWs propagate along them under action of elastic deformations, arising in the films due to the magnetic field and changing the SAWs velocity.

2 Current Sensor with Magnetically Sensitive FeNi Film

As shown in [2] for a magnetic field sensor, based on FeNi films, the change in the SAWs velocity is $\Delta V/V = 0.0035\%$ (1/30000), when the magnetic field strength changes by 10 Oe (current 1 A). The magnetic field strength near the busbar with current is defined as

$$\frac{4\pi\mu\mu_0 aj}{4\pi} = \mu\mu_0 aj = \mu\mu_0 a\frac{I}{ab} = \mu\mu_0\frac{I}{b} \tag{1}$$

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that is, we can calculate the magnetic field strength at the surface of the bus as $H = I/b$, where a is the thickness of the conductor, b is the width of the conductor, μ is the magnetic permeability, I is the current in the busbar. In a flat conductor with a width of $b = 8$ cm and a thickness of $a = 5$ mm, at a current of 10 A, the magnetic field strength is $H = 10/0.08 = 125$ A/m $= 1.56$ Oe, and at a current of 100 A, $H = 15.6$ A/m.

3 Dual-Channel Current Sensor

In contrast to the sensor design discussed in [2], this paper proposes a construction, based on magnetically sensitive films and shown in Fig. 1. It contains two mutually perpendicular channels. Therefore, if this sensor is placed on a conductive bus in such a way that the direction of the SAWs propagation coincides with the direction of the current in the bus, then in this channel the magnetic field will be perpendicular to the SAWs propagation, and in the other channel, it will be directed along the direction of the SAWs propagation. This, as shown in [3], will lead to the fact that the influence of the magnetic field on the SAW velocity will only be in the channel, in which the direction of the magnetic field coincides with the direction of the SAWs propagation.

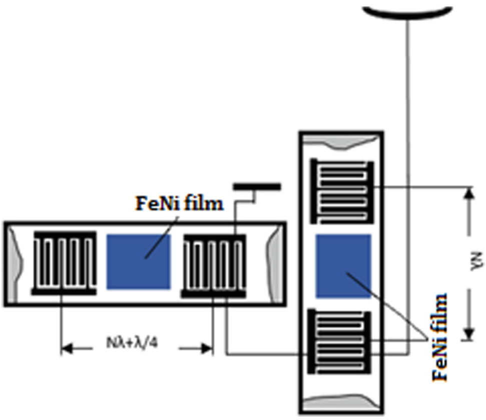

Fig. 1 Design of two-channel sensor with mutually perpendicular channels

As it can be seen from Fig. 1, the distance between the interdigital transducers (IDTs) in different channels differ by a quarter of the SAW at the central frequency. This leads to the fact that SAW, reflected from reflective IDTs, come to the receiving transmitting IDTs in the opposite phase and induce antiphase voltages in them. Therefore, there will be no signal at the antenna output (see Fig. 2). As reflected from the receiving-transmitting IDTs, the SAWs, reflected from the short-circuited grid, again fall on the reflective IDTs. However, in this case, they will again get to the receiving-transmitting IDTs no longer in the opposite phase, but in the same phase since the SAWs will pass the interval of a quarter of the length of the SAWs four times.

Therefore, the reflected signal will appear at a distance four times greater than the SAWs delay between these IDTs. If there is a current in the bus, then an additional phase shift will occur in the channel perpendicular to the current direction and the signals reflected from the reflective IDTs will no longer be in antiphase, which will lead to the appearance of a pulse response at a distance corresponding to twice the SAWs delay between IDTs (see Fig. 3).

This sensor uses ST-cut quartz substrates. The receiving-transmitting IDT has 340 pairs of electrodes, and the reflecting IDT has 260 pairs of electrodes. The central frequency is 860 MHz. The length of the magnetically sensitive film is equal to 1,000 SAWs lengths at the center frequency.

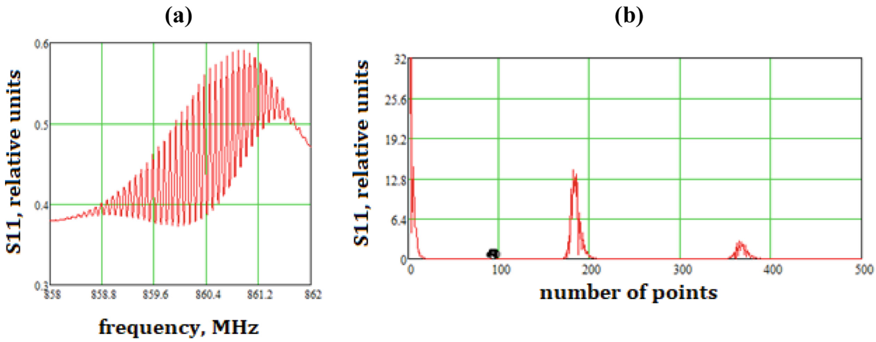

Fig. 2 Frequency (a) and time (b) dependences of the sensor parameter S11 according to Fig. 1, when there is no current in the busbar. The black dot is the location of the SAWs pulse at the primary reflection

The reader, described in [2] and based on a single frequency, is not suitable in this case, since the ripple frequency of the parameter S11 depends on the magnitude of the magnetic field (see Figs. 2a and 3a). This is because the distance between the reflected signals in the first (there is no magnetic field) and in the second (there is a magnetic field) cases is 2 times different. Therefore, at the frequency of the radio-frequency (RF) generator, the amplitude of the parameter S11 can pulsate, and not smoothly change as in the previous case. Here it is better to use the measurement of the pulse response area. To eliminate the dependence on the distance between the reader and sensor antennas, in this case, we can use a reference channel in which the parameter S11 will not depend on the magnetic field (current).

Figure 4 shows the dependence of the area of the primary pulse response on the magnitude of the magnetic field. It can be seen that the area reaches a noticeable value even at oersted units, which corresponds to thousandths of T. We can further increase the sensitivity if increase the length of the film by 2 times. In this case, the pulse response becomes noticeable even at a field of 2 Oe, which is comparable to the Earth's magnetic field (Fig. 5).

The SAW attenuation in a film with a thickness of 200 nm at a frequency of 2,450 MHz is 9.33 dB/mm [4], that is, it will be 1.6 mm at a distance between IDTs of 1,000 SAWs lengths. If we take into account that the SAW passes this section twice, we get more than 18 dB. Taking into account the attenuation in the lithium niobate itself, this attenuation

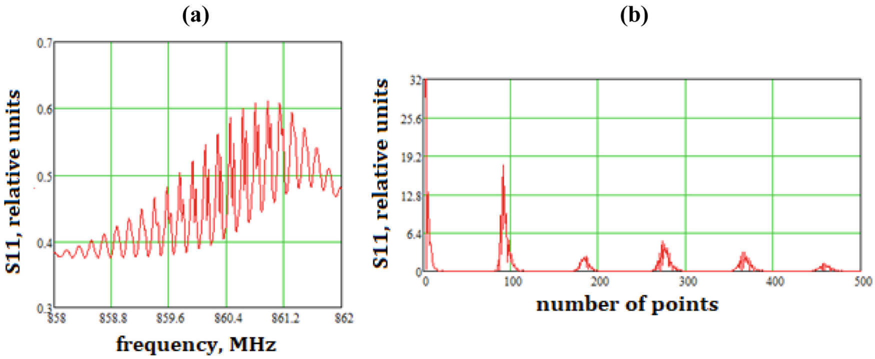

Fig. 3 Frequency (a) and time (b) dependences of the sensor parameter S11 according to Fig. 1, the magnetic field induction corresponds to 0.004 T (40 Oe)

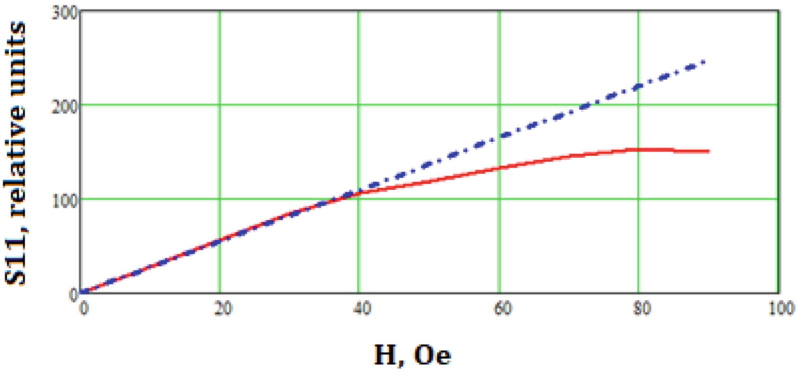

Fig. 4 Dependence of the amplitude of the primary pulse response on the magnitude of the magnetic field. The length of the magnetically sensitive film is equal to 1,000 SAWs lengths at the center frequency

will become more than 20 dB, which is completely unacceptable, since it will lead to a weakening of the signal reflected from the sensor by more than 10 times.

Therefore, it is not necessary to use lithium niobate substrates for magnetic field sensors based on magnetically sensitive films in the acoustic channel, since the increased attenuation at frequencies of 2,400–2,450 MHz due to the presence of films makes it impossible to use lithium niobate, in which the attenuation of SAW on the free surface is much lower (about 3.6 dB/μs). Therefore, it is most appropriate to use quartz in such sensors, but on more low frequency.

Calculations show that the area of the primary pulse response changes by only 0.6%, when the temperature changes by 5 °C, despite the fact that the interrogated linear frequency modulation (LFM) pulse has a band of 8 MHz with a central frequency of 860 MHz and does not depend on temperature. As the calculations show, even if the temperature changes in the range of 20–100 °C, the area of the primary pulse response will change by no more than 2%.

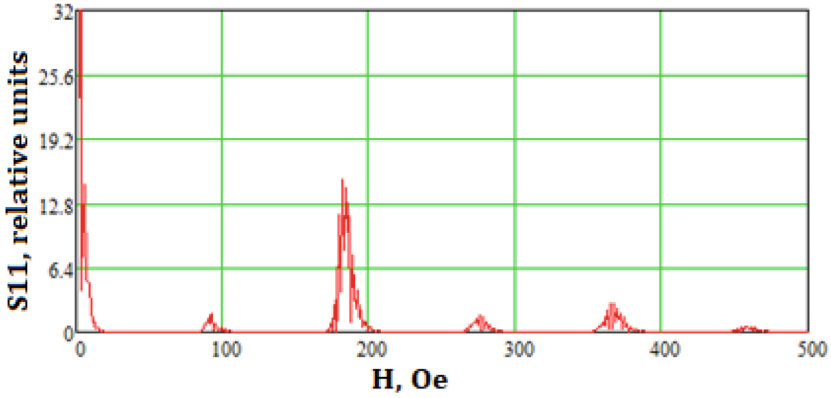

Fig. 5 Pulse response of the sensor according to Fig. 1, when there is current in the bus. The magnitude of the magnetic field induction corresponds to 0.0002 T (2 Oe)

It is also important to note that on quartz, when the temperature changes by 100 °C, the frequency will shear by only 0.28 MHz, while on lithium niobate, this shift will be 6.88 MHz. This requires a significant expansion of the frequency range for the sensors, so that the sensors, located on the buses of different phases, would not overlap the frequency ranges, that is, on lithium niobate, the center frequencies of the sensors in different phases should be located at least 7 MHz away, and on quartz only 0.28 MHz.

In this design, the use of a reference channel can be avoided. With this purpose, the secondary reflection signal can be used as a reference signal, and the primary reflection can be used as a measuring signal. Obviously, the ratio of these signals will not depend on the distance between the antennas of the reader and the sensor, but will be determined solely by the ratio of the SAWs phases that came to the receiving-transmitting IDT from the reflective IDT in dependence on the magnitude of the magnetic field (Fig. 1). Figure 6 shows the dependence of this ratio for the length of a magnetically sensitive film of 250 SAWs lengths at the central frequency.

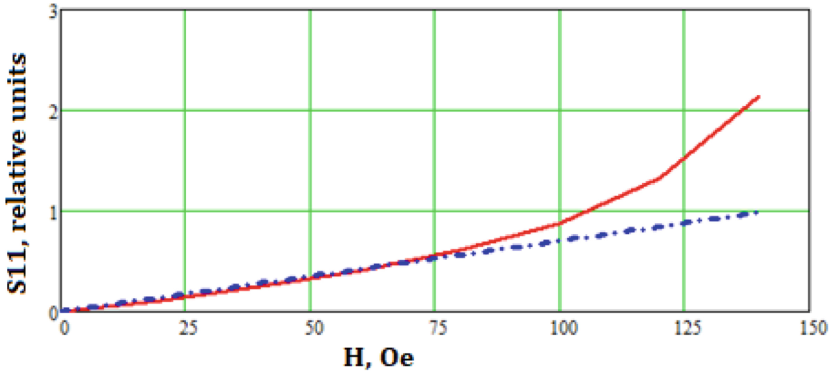

Fig. 6 Current sensor with an external impedance

Figure 6 shows that there is a linear region up to 75 E (0.0075 T), which can be expanded by reducing the length of the magnetic film.

To avoid increased attenuation in the frequency range of 2,400 – 2,450 MHz, it is necessary to use different methods to control the reflection coefficient of the signal from the sensor. One of these methods of controlling the reflection coefficient from IDT is to connect an external impedance to it, the value of which changes under the influence of a magnetic field. Thus, it was shown in [5] that under the action of fields of only a few Oe, it is possible to obtain a change in the resistance of the film by tens of percent. In [6], at a magnetic field value of 420 Oe (0.042 T) and a frequency of 500 MHz, it was possible to obtain a change in the film resistance from 0.0245 Ω (without a magnetic field) to 0.3 Ω. These films, in addition to nickel and iron, contain copper and have a layered structure. If we apply the balance circuit of the sensor (Fig. 7), then a noticeable change could be obtained in the parameter S11 even with such a change in resistance.

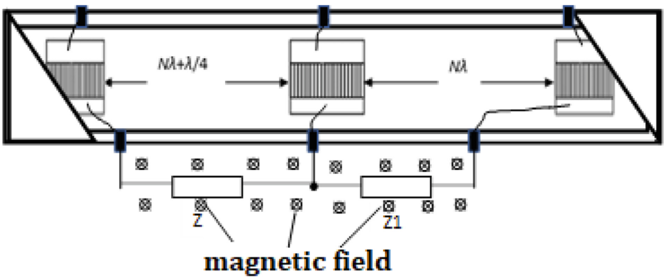

Fig. 7 External impedance current sensor

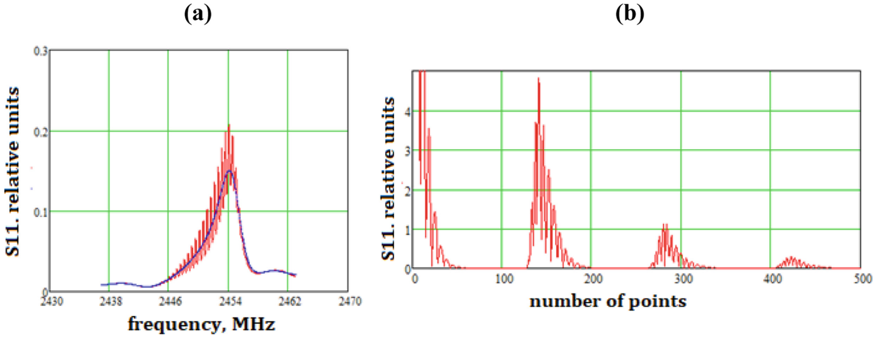

Fig. 8 Frequency (a) and time (b) dependences of the parameter S11, when the resistors in different channels differ by 10 times (the blue curve without a magnetic field)

The *Z* and *Z*1 impedances are a series-connected capacitances, inductances, and resistors. Moreover, in one channel, the resistor is sensitive to the magnetic field, and in the other channel, the situation is opposite. All the parameters of the impedances both on the right and on the left in the absence of a magnetic field are the same. When the magnetic field is switched on, the resistances become different, the balance is disturbed,

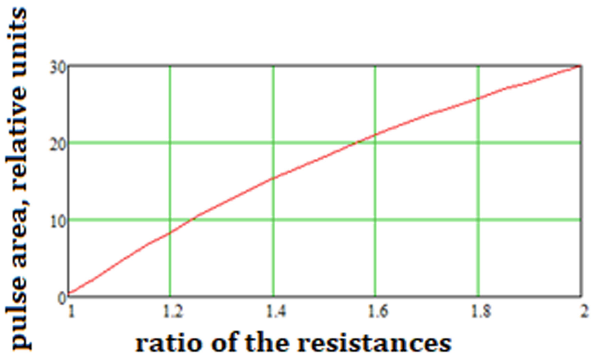

Fig. 9 Dependence of the pulse response area on the resistance ratio

and the reflected SAWs no longer compensate for each other, that leads to a ripple of the parameter S11 (see Fig. 8).

Figure 9 shows the dependence of the change in the pulse response area on the resistance ratio, when the magnetic field changes. In this case, a reference channel is needed to eliminate the dependence on the distance between the antennas.

Since such a sensor is performed on the YZ-cut of lithium niobate, a distance of more than 5,000 SAWs lengths can be made between IDTs. In addition, for each phase, we must select a different range, within which the frequency band for the interrogating LFM pulse is selected. Since the band in the range of 2,400–2,483 MHz is 83 MHz, it can be divided into three sub-bands with a bandwidth of 27 MHz. Within each band, the frequency swing band of the LFM pulse will be equal to 26 MHz. Then, if the center frequency changes due to temperature, even by 100 °C, the sensor's operating range will not go beyond the specified sub-bands.

4 Conclusion

A two-channel version, based on the dependence of the SAW velocity in the film on the magnetic field, is proposed. With this method, it is possible to work on both quartz and lithium niobate substrates. There is no need for a reference channel. However, it is impossible to work at frequencies above 1 GHz because of the large attenuation in magnetically sensitive films.

For operation in the range of 2,400–2,483 MHz, it is necessary to use a balanced circuit, where one of the reflective IDTs are electrically loaded on the impedance, the value of which depends on the magnetic field.

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