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Simulation of acoustic wave devices using Matlab

***Abstract**. A review of the principles and applications of surface acoustic wave (SAW) devices is given. An implementation of a design method for SAW devices using MATLAB is described. Results of a comparison between the proposed simulation technique and experimental test results are presented.*

***Streszczenie.** Przedstawiono zasadę działania i wykorzystanie urządzęń typu SAW (urządzenia z akustyczną fala powierzchniową). Zaproponowano metody projektowania murządzęń z wykorzystaniem platformy MATLAB. (**Symulacja pracy urządzeń SAW z wykorzystaniem programu Matlab**)*

Keywords: Surface Acoustic Wave Device (SAW), Simulation, Matlab, CVD Diamond.
Słowa kluczowe: SAW – powierzchniowa fala akustyczna, Matlab.

Introduction

The propagation of a mechanical vibration on the surface of a solid (a surface acoustic wave or SAW) was described in the 19th century by Lord Rayleigh. These waves are similar to longitudinal seismic waves, in the sense that they only penetrate solids up to a depth of the order of magnitude of the wavelength, they undergo little attenuation as they progress on the surface, and the movement of particles in the solid is elliptical. These waves can be coupled to any medium in contact with the surface. If, on the other hand, the medium where the waves propagate is piezoelectric, an electric signal can be transduced into a mechanical vibration, thus opening the possibility of a device based on SAWs to be used as an electronic component.

The capabilities of SAWs were further enhanced through the invention of the interdigitated transducer, or IDT [1], which can convert an electric signal into a Rayleigh wave, and vice-versa. The IDT is thus reversible, that is, it can operate both as an emitter or a receiver.

The simplest, most obvious application of a SAW device is as a delay element: one can apply an electrical signal to an IDT at one end of a slab of piezoelectric material, and convert the delayed mechanical signal back into an electric signal at the other end convert the delayed mechanical signal back into an electric signal at the other end.

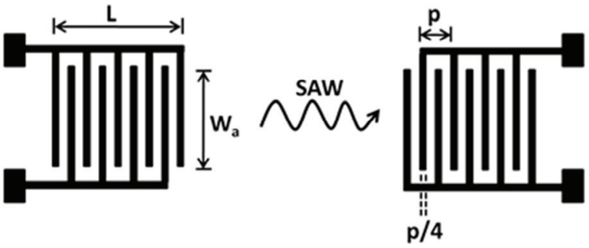

Fig. 1 A SAW device in the form of a slab with an IDT at either end.

The delay times available with this kind of device are difficult to obtain by other means, for instance, using conventional electronic components. In fact, the propagation velocities of Rayleigh waves in common piezoelectric materials, such as quartz, are of the order of 3000 m/s, thus making delay times of milliseconds possible with reasonable dimensions, a desideratum that would be hard do achieve using classic delay lines with either lumped or distributed elements. On the other hand, the dimensions of IDTs for frequencies at the low end of the microwave region (from about 300 MHz to over 1 GHz) are of the order of microns, making the fabrication of SAW devices accessible through conventional lithographic techniques.

IDTs can also be configured as reflectors through the use of an appropriate electrical load, making it possible to obtain a large variety of responses by making use of the interference between incident and reflected waves. This has given rise to a wide choice of devices, which have been commercially available for several decades, such as resonators, RF and IF filters, thus replacing in many instances much bulkier components that used to be implemented with reactive components. Most transmitters and receivers nowadays use massive quantities of SAW devices. It can be stated that the small, lightweight cell phones of today would not be possible without extensive use of these devices. It is no wonder, therefore, that the market for SAWs is largely dominated by the components industry. It is estimated that the electronics industry consumes about 3×10^9 of these devices yearly.

The use of SAWs as sensors is more recent, dating from about the early 1990's. Their use as temperature sensors is obvious, because the propagation velocity may be sensitive to temperature depending, of course, on the characteristics of the piezoelectric material and the angle of cut with respect to the crystallographic axis. Also obvious is the use of SAWs as strain/stress sensors. In fact, the propagation velocity is sensitive to the deformation state of the substrate material, and many devices using this effect have been designed and are even commercially available.

Typical Applications of SAWs

A vast variety of other sensors is possible, using the property that mechanical vibration can be coupled to any material deposited on the surface of the substrate. The device can be coated with the relevant material, whose mass, for instance, is affected by adsorption of gases or liquids on the surface, which in turn changes the propagation characteristics of the device. This opened the possibility of designing several kinds of mass, chemical, humidity, gas and other sensors based on SAW devices.

SAWs have also been used with success as RFID tags. In fact, a coded sequence of reflectors can be designed into the device, thus making it possible to assign a unique code word to each device. This type of tag has been used with success in cars at tollgates, trains, and also as a replacement for the more conventional barcode labels [2][3][6].

SAW-based RFIDs and sensors, or combinations therewith, have many advantages: i) they are wireless devices, in the sense that they can be remotely interrogated by means of an RF beam. In fact, the input generator can very well be an antenna whose dimensions, for the frequencies involved, does not need to be much longer than a few centimeters; ii) being passive devices, they do not need any kind of power supply, as they can derive power directly from the interrogating beam; iii) they can be easily integrated with existing technologies, e. g., integrated circuits, microelectromechanical devices (MEMs); they can be made immune to many environmental aggressions, namely humidity, temperature and chemical agents; iv) they can be interrogated in real time (fast response); and, v) because they can be produced in large quantities through the use of lithography techniques, the per-unit cost is very low.

These properties make SAWs a good choice for a wide variety of sensing and measurement applications. SAWs have been used for sensing under extreme or aggressive conditions, namely measurements on inaccessible or moving parts, measurements under toxic, radioactive or contaminated locations.

Through changes in the basic structure, SAWs can be made to respond to a wide variety of physical magnitudes. The most obvious is perhaps temperature, as mentioned above, but strain and stress are also possible measurands, as the deformation of the substrate changes the propagation velocity of Rayleigh waves on the surface. If the substrate surface is coated with a film capable of adsorbing fluids, SAWs may also respond to various chemical substances, such as CO, CO_2, NO_x, H_2 and a wide variety of organic molecules, including poison gases. They can even be made to respond to the growth of bacteria and biological substances such as DNA.

Finally, probably the most obvious application of SAWs is their use as radiofrequency identifier (RFID) tags, with the advantage of smaller dimensions and near invisibility. In this application, SAWs may very well replace the common bar-coded tags in the near future. And, of course, the RFID and sensing functions can be combined in the same device.

Real life examples of the use of SAWs as sensors in the last few years are already in the literature.

For instance, as is well known, remote measurement of tire pressure in high-end automobiles is already in commonplace use by several manufacturers [3].

The temperature on the surface of train brakes is also already in current practice [2].

Various kinds of gas detection devices in the auto, aeronautical and space industries have been reported as well [4].

Another interesting application is the measurement of both temperature and pressure inside the combustion chamber of thermal engines, under test conditions. Of course, in order for the radiofrequency beam to be able to access the device, an antenna has to be mounted inside the crankcase, which is no problem on the test bed. This type of setup has been successfully tested [5].

Chemical warfare agents and landmine debris also have been successfully detected [6] [7].

A very recent application is the integrated monitoring of volatile gas contamination in NASA satellite and space vehicle assembly facilities [8].

Practical aspects

Both the devices and the associated equipment, such as the antennas and the readout unit can be made very small, which makes them very attractive for a myriad of applications. In fact, the velocity of the mechanical (acoustic) waves in the most common substrates used in these devices, such as Lithium Niobate ($LiNbO_3$), Lithium Tantalate ($LiTaO_3$), quartz (SiO_2) and Langasite ($La_3Ga_5SiO_{14}$), lies in the vicinity of $10^{-5}c$, where $c \approx 3 \times 10^{-8}$ m/s.

This gives, at the frequencies allocated in the ISM (industrial, scientific and medical) radio bands of 433.92 MHz, 915 MHz and 2.45 GHz, a mechanical wavelength slightly above 1 μm or a few μm, which is convenient both for ease (and low cost) of fabrication. As for the devices themselves, their size depends on the number of fingers in the IDTs and on other aspects, namely, the desired accuracy on the measurement of a given delay. Delays larger than 1 μs are perfectly possible with a device 5 mm in length, which does not put very stringent requirements on the readout electronics.

On the other hand, the RF wavelength at these frequencies is quite manageable: at 915 MHz, for instance, the open-space RF λ is about 33 cm, making monopole antennas with lengths around 7 or 8 cm feasible [9].

If useful information is to be gathered from a SAW device, a readout electronic unit must be designed and built. This is a quite established technology, because, as must be obvious from the preceding discussion, a SAW sensing system is very similar to a radar system: the device is excited by an RF beam and responds, after a delay, with a similar signal (an echo). The delay contains information about the physical magnitude to be measured. Under these circumstances, many of the building blocks already available for radar systems can also be used in SAW sensing or identification (ID) systems. Equally available are many of the techniques already in use for signal recovery and decoding.

Most of the readout systems in use fall into one of two categories: time sampled and frequency sampled. In the first category, signals are sampled in the time domain, and the information is immediately available for analysis and/or storage. In the second category, an inverse Fourier transformation is performed on the reflected signal and is later stored in digital or analog form. Coherent detection or optimal filtering can be performed on the response signal, because an original version of the transmitted signal is available.

Simulation techniques

In order to be able to predict the behavior of a sensing or ID system based on SAWs, a suitable model must be available, along with adequate software tools. Fortunately, the behavior and modeling of typical SAWs is a task that has been under investigation for a long time, and there are excellent texts on the subject [10]. Several models have been developed, but the most useful one, from an electronic designer's point of view is the so-called crossfield model, where the IDT can be modeled by the circuit in Fig. 2

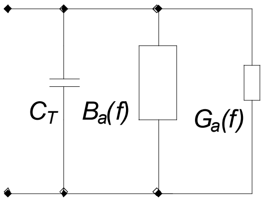

Fig. 2. Model used in the simulation.

In this figure, C_T represents the total capacitance of the IDT, $G_a(f)$ the radiation conductance and $B_a(f)$ the acoustic susceptance.

With such a simple model, there is no need to implement specific software for the simulation. The simulation technique consists basically of the implementation of the equations in Matlab. These are basically the equations in [11]. The IDT frequency response is given by

$$|H(f)| = 2k\sqrt{C_s f_0} N_p \frac{\sin X}{X} exp\left(\frac{\omega j 2\pi f N_p}{2 f_0}\right) \tag{1}$$

where: f_0 — center frequency; N_p — number of finger pairs; k — piezoelectric coupling coefficient; C_s — capacitance of a finger pair per unit length, and

$$X = N_p \cdot \pi \cdot \frac{f - f_0}{f_0}\ .$$

Now the global IDT response is given by the product of the transfer functions of both IDTs:

$$H_T = H_1(f) \cdot H_2(f) \tag{2}$$

The real part of the input admittance is given by

$$G_a(f) = 8k^2 \cdot C_s \cdot W_a \cdot f_0 \cdot N_p^2 \cdot \left|\frac{\sin X}{X}\right|^2 \tag{3}$$

and the insertion loss is

$$IL(f) = -10\log\left(\frac{2G_a(f) \cdot R_g}{\left(1 + G_a(f) \cdot R_g\right)^2 + \left(R_g \cdot \left(2\pi \cdot f \cdot C_T + B_a(f)\right)\right)^2}\right)$$

For an optimum design the effective finger width must be adjusted to

$$W_a = \frac{1}{R_{in}} \cdot \left(\frac{1}{2f_0 \cdot C_s \cdot N_p}\right) \cdot \frac{4k^2 \cdot N_p}{\left(4k^2 \cdot N_p\right)^2 + \pi^2} \tag{4}$$

In order to test the accuracy of the approximations made, a simulation was run on a commercial device by Sawtron (www.sawtron.com), a bandpass filter for which some design information was available (type S321273).

The results are presented in Figures 3, 4 and Table 1.

Although the comparison of pictures doesn't seem very accurate, mostly due to second-order effects that weren't taken into account, such as finger overlap, the agreement between the figures advertised by the manufacturer, measured and simulated, in the table, is quite good.

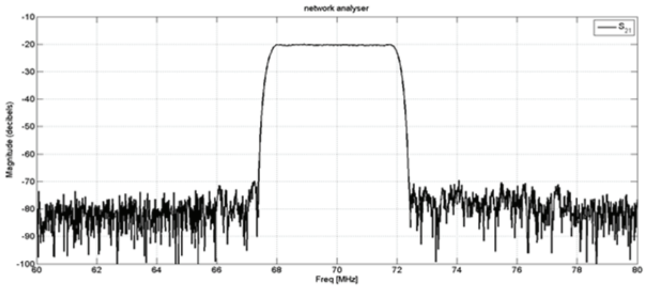

Fig. 3. Measured response of real device (Sawtron type S321273). Network Analyzer: HP 4753D

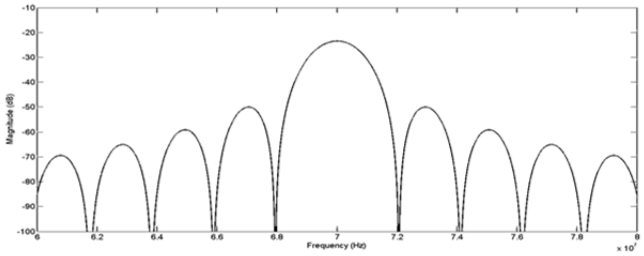

Fig. 4. Simulated response of the same device, based on the available information.

Table 1. Comparison of results

	Datasheet	Measured	Simulated
f_0	69.9669 MHz	70 MHz	70 MHz
BW	4.2 MHz	4.2 MHz	4.2 MHz
IL	20.21 dB	20 dB	23.47 dB

Current work: use of diamond in SAWs

In diamond, carbon atoms are arranged in a cubic lattice. Diamond is thus not piezoelectric, so that it cannot be used by itself in SAW devices. However, it has some very remarkable properties. As is well known, it is the hardest material known. It has a very high Young modulus, about 100 GPa. It is chemically inert, and resistant to most acids and bases. Although it is an almost perfect electric insulator, it has very high thermal conductivity (22 W/(cm·K)). It has a high bandgap (5.4 eV) and a very high breakdown electrical field (10^4 kV/cm).

These properties make diamond a very tempting material to use in SAWs, either as a protective material or as the acoustic wave-propagating medium itself. In particular, the high Young module leads to a much higher velocity of mechanical waves (approximately 15 km/s, instead of around 3 km/s for most of conventional piezoelectric materials).

Therefore, the idea of depositing a diamond film on SAWs looks appealing, although it presents some difficulties.

Various techniques have been proposed to deposit diamond in a substrate. Artificial crystals can be made using high-pressure high-temperature techniques (HPHT). For the deposition of thin films, chemical vapor deposition (CVD) techniques are preferred. They are technologically simple and versatile; they permit the deposition of diamond on shapes with complicated geometries; and they don't require expensive setups or equipment.

In simple terms, all that CVD requires is a reactor with a carbon-containing species (typically methane, ethanol or graphite) and an energy source. This can be a hot filament or a microwave source.

A typical fabrication setup, after the choice of a suitable substrate, would start with the deposition of the IDTs, the fabrication of the antenna (this can eventually printed on the substrate itself) and then coating the whole device with a diamond film with suitable thickness.

Compared with other techniques, which are based on depositing a piezoelectric substrate on a diamond film, this reversed fabrication process presents many advantages.

Because the acoustic wave only penetrates the substrate up to a depth of the order of magnitude of the wavelength, the propagating medium would be the diamond. Propagation velocity being much higher in the diamond, this would, as a consequence, permit the use of higher finger widths in the IDTs for a given frequency (thus relaxing the requirements for lithography), or alternatively, the use of higher frequencies for the same lithography resolution.

Due to the high thermal conductivity of diamond, it can function more efficiently in conjunction with a heatsink, thus permitting higher operating temperatures and/or higher operating power.

The diamond film can, in addition, function as a protective coating against aggressive or harsh environments. It can also be used as a sensing film in some circumstances.

Besides the need for further investigations on deposition techniques suitable for deposition of diamond films on the materials most commonly used in SAWs, additional studies are needed in order to develop simulation techniques adequate to a layered structure such as the one we are proposing. In particular, the effect of coupling between the mechanical vibration in the piezoelectric substrate and in the diamond film and, most importantly, the interference between the waves in both media, along with the resulting velocity, are not well known and need further study and experimenting.

A simplified approach would be, as long as the diamond film is reasonably thicker than the expected wavelength of the Rayleigh wave, to use the parameters of diamond in all calculations, but this needs confirmation and eventually the development of new simulation tools.

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