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Surface Acoustic Wave Devices in Communications

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Operating principles and analyses of transversal surface acoustic wave (SAW) devices are reviewed. Design procedures are given for different types of devices such as bandpass filters, delay lines and dispersive delay lines. Their capabilities and their wide and diverse applications in communications are also presented.

Key words: **SAW device, transversal filter, SAW filter, RAC filter, delay line, telecommunications.**

Introduction

IN the last thirty years surface acoustic wave (SAW) devices have found diverse applications in consumer and highly professional electronic devices and systems. This was possible above all due to the fact that they can perform different functions in the frequency range from 10 MHz to several GHz. They can be used as bandpass filters, delay lines with constant or dispersive delays, matched filters, compressors, expanders, convolvers and correlaters. In some frequency domains where high Qs are needed they are irreplaceable. They have small size, compact structure, outstanding stability, and their fabrication is compatible with the integrated circuits technology [1-10]. There only disadvantage is high insertion loss, even 20dB, but using special techniques it can be lowered.

Surface acoustic waves were discovered in 1885 by Lord Rayleigh, and are often named after him: Rayleigh waves. A surface acoustic wave is a type of mechanical wave motion which travels along the surface of a solid material. Rayleigh showed that SAWs could be used for the explanation of one component of the seismic signal due to an earthquake, a phenomenon not previously understood. The velocity of acoustic waves is typically 3000 m/s, which is much lower than the velocity of electromagnetic waves. In 1965 White and Voltmer actually invented SAW devices. They found out how to launch a SAW in a piezoelectric substrate by an electrical signal. Starting around 1970, SAW devices were developed for pulse compression radar, oscillators, and bandpass filters for domestic TV and professional radios. In the 1980s the rise of mobile radio, particularly for cellular telephones, caused a dramatic increase in demand for filters. New high-performance SAW filters emerged and vast numbers are now produced, around 3 billion annually. In the last two decades SAW devices have found numerous different applications outside their conventional fields of application: communications and signal processing. In the last decade considerable work has been done in the development of SAW sensors of different types of high quality. SAW devices are used as temperature, pressure and stress sensors as well as chemical and biosensors [11, 12]. SAW sensors are also used for wireless monitoring in harsh environment.

The first part of this paper deals with the principles of operation, analysis and design methods of SAW devices. In the second part different types of SAW devices and their applications in communications are presented. The capabilities and limits of modern filters are also discussed.

Principle of operation

The operation of the SAW device is based on acoustic wave propagation near the surface of a piezoelectric solid. This implies that the wave can be trapped or otherwise modified while propagating. The displacements decay exponentially away from the surface, so that the most of the wave energy (usually more than 95%) is confined within a depth equal to one wavelength. The surface wave can be excited electrically by means of an interdigital transducer (IDT). A basic SAW device consists of two IDTs on a piezoelectric substrate such as quartz, Fig.1. The input IDT launches and the output IDT receives the waves.

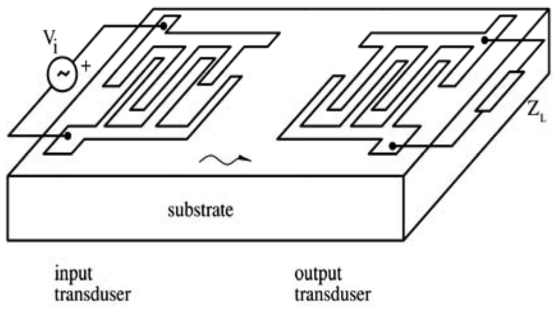

Figure1. The basic structure of a SAW device.

The interdigital transducer consists of a series of interleaved electrodes made of a metal film deposited on a piezoelectric substrate as shown in Fig.1 [1-10]. The width of the electrodes usually equals the width of the inter-electrode gaps giving the maximal conversion of electrical to mechanical signal and vice versa. The minimal electrode width which is obtained in industry is around 0.3μm, which

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determines the highest frequency of around 3 GHz. The commonly used substrate crystals are: quartz, lithium niobate, lithium tantalate, zincoxide and bismutgermanium oxide. They have different piezoelectric coupling coefficients and temperature sensitivities. ST quartz is used for most temperature stable devices. A sinusoidal voltage v of frequency f applied to the input IDT forms an electric field which, through the piezoelectric effect causes a strain pattern of periodicity $2d$, where d denotes the distance between the centers of the electrodes. If the frequency f is such that $2d$ is close to the surface wave wavelength, a surface wave will be launched in two opposite directions away from the transducer. The surface wave causes the corresponding electric field in the second transducer and correspondingly the voltage at the impedance Z_L. The wave velocity is a function of the substrate material and is in the range of 1500m/s to 4800m/s, which is 10^5 times lower than the electromagnetic wave velocity. This enables the construction of a small size delay line of a considerable delay. The input and output transducers may be equal or different. It depends upon the function which the SAW device has to perform. Usually they differ in electrode overlaps, number and sometimes positioning. The magnitude of the output signal is the function of the ratio of the signal wavelength and the distance 2d. If the distance 2d is equal to the wavelength, the magnitude of the output voltage is maximal. The corresponding frequency is then called central or synchronous frequency of the device. The magnitude of the output voltage decays as the frequency shifts from the central frequency. It means that basically a SAW device is a transversal bandpass filter. In transversal filters the phase characteristic is a function of the distances between the electrodes and the amplitude characteristic is a function of the electrodes number and lengths. If the electrodes are uniformly spaced as in Fig.1, the phase characteristic is a linear function of frequency, e.g. the delay is constant in the appropriate frequency range. The IDT geometry is capable of almost endless variations, leading to a wide variety of devices. In the second type of SAW devices – SAW resonators, IDTs are only used as converters of electrical to mechanical signals and vice versa, but the amplitude and phase characteristics are obtained in a different way. In resonators the reflections of the wave from either metal stripes or grooves of small depths are used.

Analysis of SAW transversal devices

There are three methods for the analysis of SAW transversal filters. The first and the most accurate one, giving also the exact proof of the previous statements, starts from the second Newton's law. The wave equations are the partial differential equations of the form [2, 3, 8, 9]:

$$\rho \frac{\partial^2 u_m}{\partial t^2} = \sum_{j=1}^{3} \frac{\partial T_{mj}}{\partial x_j}, \quad m = 1,2,3 \tag{1}$$

where:
ρ is the density of the substrate,
u_m is displacement in the direction x_m,
T_{mj} is the component of the stress tensor,
x_j's are space coordinates and t is time.

They have to be solved using the boundary conditions, Maxwell's equations and the relations between the mechanical and electrical variables of the piezoelelectric substrate [2, 4, 8, 9]. Since the electrodes are thin and narrow, the mechanical boundary conditions can be simplified but the electrical ones are very complex. Namely, on the surface between the electrodes there are no free charges, the potential of all interconnected electrodes must be the same, the currents in the two sets of electrodes are equal in amplitude and opposite in phase and the currents and the voltage must satisfy the appropriate conditions given by the external circuits. Because of that the exact analysis even in the case of uniform transducers with small number of electrodes is very complex and the solutions can be found only numerically. This method was used to determine the minimal number of electrode pairs for efficient conversion of input electric to wave power. It was shown that for 10 electrode pairs, conversion is sufficient, over 95%.

Therefore, other simplified methods, more or less approximate, are derived and used. The widely used method of the analysis is based on an equivalent circuit model for a single electrode section of an IDT. [1-7, 13-26]. Usually very simple, the so-called "crossed-field" equivalent model [9, 10, 13] is used, yielding very good results for the uniform IDTs with eqal lengths of electrodes. However, for nonuniform IDTs, a more complicated, so-called "variable" model should be used in order to include an acoustic wave impedances difference between the electroded and unelectroded regions of the transducer. One electrode section and its variable model are presented in Fig.2 [2, 8, 9]. The model is a three-port network with two acoustic and one electric port.

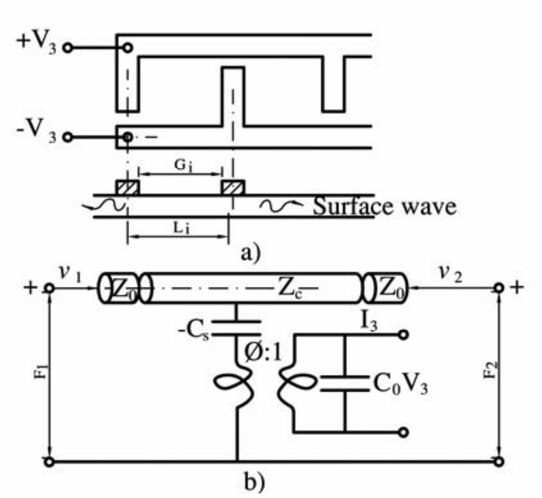

Figure. 2. One electrode section a), its equivalent model b).

The acoustic variables are: velocities v_1, v_2, and forces F_1, F_2. The electric variables are: the current i_3 and the voltage V_3. Z_0 is the characteristic acoustic impedance of the free surface of the substrate, Z_C is the acoustic impedance of the substrate under the electrode, and ϕ is the turns ratio of an acoustic to electric circuit transformer. Z_0, Z_C, ϕ, C_s, and C_0 are the functions of the ratio $(L_i - G_i)/G_i$ and the piezoelectric properties of the substrate. The whole transducer is represented by a set of such single electrode sections connected electrically in parallel and acoustically in cascade. Using the model, algorithms for analysis of very complex nonuniform transducers were developed [17-21] giving very good results. The efficiency of the algorithms has been considerably improved by computer-aided symbolic analysis [27, 28] implementation. If the parameter γ equals to 1 the model becomes the "crossed field" model (according to the electric field pattern). From the "crossed field" model the input impedance of the uniform transducer as seen at its electrical port is of the form:

$$Z(f) = \left[G_a(f) + jB_a(f) + j2\pi fC_T\right]^{-1} = \\ = R_a(f) + jX_a(f) + (j2\pi fC_T)^{-1} \quad (2)$$

where:

$$G_a(f) = 2f_0C_0k^2\left(tg\frac{\theta}{2}\sin\frac{N\theta}{2}\right)^2 \quad (3)$$

$$B_a(f) = f_0C_0k^2tg\frac{\theta}{2}\left(2N + tg\frac{\theta}{2}\sin N\theta\right) \quad (4)$$

$$\theta = \pi f / f_0 \quad (5)$$

$$C_T = NC_0 \quad (6)$$

f_0 is the synchronous frequency and N is the number of electrode pairs. Fig3 shows the form of $G_a(f)$ and $B_a(f)$ [3, 8] for N=10, $k^2 = 0.043$, and $R_a(f_0) = 50\Omega$.

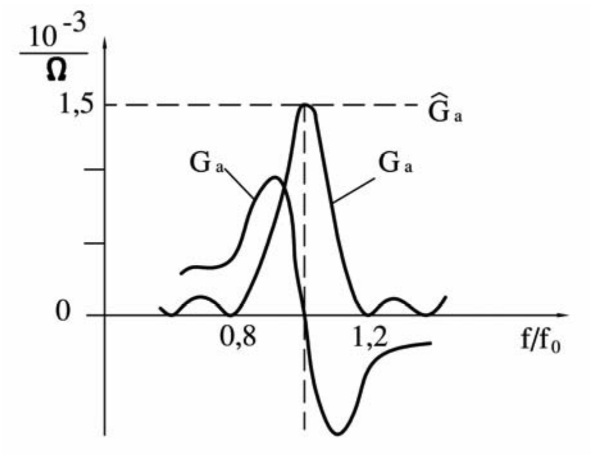

Figure 3. Frequency dependence of the input admittance.

If the ohmic losses are small the acoustic power radiated is the power dissipated in the resistive part of the equivalent input impedance, thus giving the conversion loss and the bandwidth of the transducer. To minimize the conversion loss, $R_a(f_0)$ is made equal to the generator impedance R_g, and the reactive part of the impedance at the frequency f_0 is cancelled by an inductor. For relatively large values of N the bandwidth Δf is approximately f_0/N. For small values of N the bandwidth Δf is given by:

$$\Delta f / f_0 = 2\pi f_0NC_0R_a(f_0) \quad (7)$$

The maximal relative bandwidth is determined by the substrate and equals to $2k/\sqrt{\pi}$, giving an optimal number of electrode pairs. Larger bandwidths can be obtained using N less than optimal and special matching networks.

The third method of the analysis is the "δ function method" [2]. Since the electric fields, induced by the applied voltage in the gaps between the electrodes, are largest at the electrode edges, they can be regarded as a pair of delta functions in each gap as shown in Fig.4. Each delta function will launch a surface wave uniformly along the electrode if the electrode length W is big enough. Then the analysis simplifies to summation of these surface waves. At the output transducer each inter-electrode

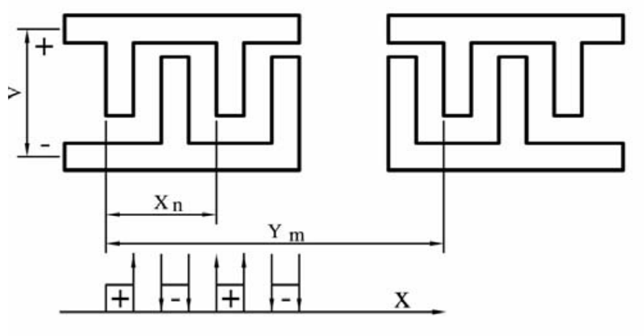

Figure 4. δ function model

gap can be regarded as a "tap" of a delay line. The output signal is then given by the sum of all waves launched from the input transducer at all electrodes of the output transducer. Since each launched signal has the form $e^{j\omega(x_n-x)/v_s}e^{j\omega t}$ the transfer function $H(f)$ is given by [2, 8, 9]:

$$H(f) = \frac{V_0}{V_i} = \sum_{m=1}^{M}\sum_{n=1}^{N} I_nI_me^{j(x_n-y_m)2\pi f/v_s} \quad (8)$$

where: v_s is the velocity of the waves, M and N denote the number of electrode edges of the output and input transducer, respectively, and I_n, I_m are the coefficients proportional to the electric field at the corresponding edge. I_n and I_m are the functions of the electrode geometry and their signs depend upon the sign of the bus bar they are connected to (V^+ or V^-). If the transducers have uniformly spaced electrodes with equal lengths, all coefficients I_n and I_m have the same values and then the double sum in (8) can be represented as a product of two independent sums in n and m. Then it can be noticed that

$$\sum_{n=1}^{N} I_ne^{jx_n\omega/v_s}$$

is actually the Fourier transform of

$$\sum_{n=1}^{N} I_n\delta(x - x_n).$$

This gives the idea for a very effective design of SAW devices. In order to get the proper form of the transfer function, the amplitudes of the δ functions have to have proper amplitudes A_n. This cannot be achieved, but the same final result is obtained if the electrode overlap W is changed appropriately. In that case the function has the same amplitude but the launched energy is proportional to the overlap W. Then the transfer function has the form:

$$H(f) = \sum_{n=1}^{N}\sum_{m=1}^{M} C_{nm}I_nI_me^{j(x_n-y_m)\omega/v_s} \quad (9)$$

where $C_{nm} = \min\left\{w(x_n), g(y_m)\right\}$ and $w(x_n)$, $g(y_m)$ are the overlap functions of the input and output transducers, respectively. The use of different overlaps in the transducer is known as apodization. Now the double summation cannot be represented as a product of two sums since C_{nm} is the function of both n and m. However, if one of the transducers has a small number of uniformly spaced electrodes, the transfer function can be represented in a simpler form:

$$H(f)=\left(\sum_{n} w(x_n) I_n e^{jx_n\omega/v_S}\right)\gamma \qquad (10)$$

where: $\gamma = const.$ is the function of the uniform transducer, and $w(n)$ and I_n are the parameters of the apodized, non uniform transducer.

The bandwidth and the central frequency obtainable with SAW devices are strongly influenced by the quality of the fabrication process. The fabrication is very similar to photo etching techniques used in semiconductor industry, e.g. after evaporation of a metal film (aluminum or gold), photo resist is deposited, exposed through a mask and developed, and the unwanted metal is then chemically etched. The minimum obtainable line width, e. g. maximal frequency, is determined by the quality of the lithographic process. The conventional contact printing limits the minimum line width to 2 μm. Conformable contact printing gives the minimum line width of 0.4 μm, while the electron beam lithography lowers the limit to 0.1 μm. The minimum centre frequency obtainable is determined by diffraction and the width of the substrate. The fractional bandwidth obtainable is also dependent on the type of the substrate and the device. It is typically 2 to 30%. Higher bandwidths can be obtained using special techniques.

Design of transversal SAW devices

Design of transversal SAW devices is very complex so that it could not be done without a computer. Generally the design procedure consists of the following steps:

a) choice of the substrate and the types of IDTs,
b) determination of the coefficients of the impulse response of the apodized IDT,
c) determination of the apodization law,
d) determination of the matching network and the absolute apodization function,
e) determination of the geometries of the IDTs and the whole filter.
f) Verification through characteristics calculation.

The choice of the substrate and the type of IDTs depends upon the type of device and its requirements. Mainly the lithium niobate and ST-cut quartz substrates are used. The lithium niobate has a higher electromechanical coupling coefficient and therefore is preferred for low insertion loss and wide band filters and delay lines. ST quartz has a lower coupling coefficient but has substantial advantages in respect to the influence of the second order effects, e. g. lower bulk wave generation, lower acoustic reflections and better temperature stability. There are three types of SAW transversal devices: bandpass filters, constant delay lines and dispersive delay lines. In SAW bandpass filters IDTs have uniformly spaced electrodes and the desired characteristic is tailored by apodization. Bandpass filters IDTs can be designed only with two IDTs or with two IDTs and a multistrip coupler between them [2, 29-31]. In the first case one IDT is unapodized with a small number of electrodes, and the second one is apodized accordingly to the desired transfer function. In the second case both transducers are apodized, but only lithium niobate can be used. Bandpass filters are designed using the known methods of FIR digital filters design. SAW delay lines of constant delay consist of two usually identical unapodized IDTs with small number of uniformly spaced electrodes [2, 32]. The distance between the first electrodes of the transducers determines the delay. Dispersive delay lines consist of one uniform, unapodized IDT and one apodized IDT with electrode spacing linearly decreasing or increasing, as shown in Fig.5 [2, 33, 34]. In dispersive delay lines delay linearly decreases or increases in the frequency range. It is actually a special type of the matched filter - matched to the frequency modulated signal.

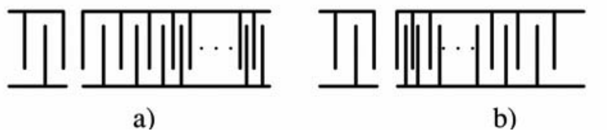

Figure 5. Dispersive delay lines a) expander, b) compressor.

The design of dispersive delay lines is the most complex one. The starting point for the second step is the linear FM (chirp) impulse response. The electrode positions and the apodization law are determined from it. The matching network and the absolute apodization function are defined according to the specified requirements concerning losses, triple transit echo suppression and impedances of the generator and load. Dispersive delay lines can be also made using small grooves or metal stripes as reflectors [2, 35-39. 42]. This type of dispersive delay line is called the reflective array compressor (RAC). In that case the IDTs are simple, uniform with a small number of electrodes and the desired characteristic is obtained by varying the distance between the reflectors.

Applications

One of the first applications of SAW bandpass filters in communications was in television receivers as MF filters. They are still used in all TV systems (PAL, SECAM, NTSC), as well as in satellite, cable TV and HDTV systems. SAW bandpass filters are used in space communications, digital optical communications, GPS receivers in L band, mobile telephony, and digital Europe GSM network. Modern SAW filters have central frequencies in the range of 10 MHz to 4.4 GHz, passbands from 50 kHz to 70% of the central frequency. Typically losses are in the range of 3 to 20 dB, and out of band signal rejection of 60 dB. The phase error is ±2°, and the passband loss variation 0.05 to 0.5 dB. The frequency response of the SAW bandpass filter P/N:WBX2698P for digital audio broadcasting is presented in Fig.6 [40].

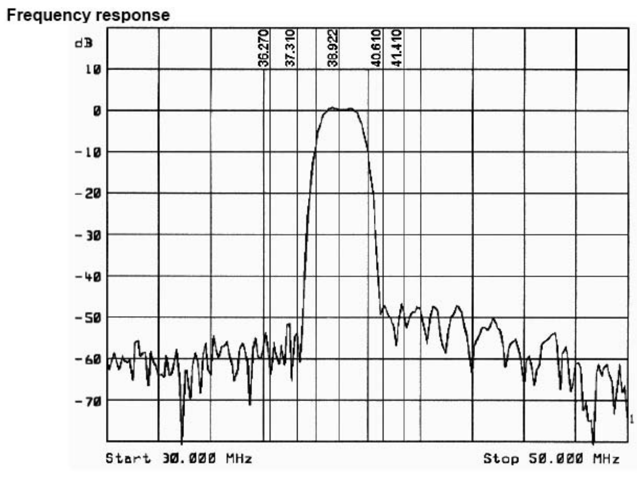

Figure 6. Frequency response of the SAW bandpass filter P/N:WBX2698P [40].

SAW delay lines are made for central frequencies in the range of 10 MHz to 2 GHz, with relative passbands up to 66%. The delay depends of the frequency range: it could be even $100\mu s$ in the range of 100 MHz, but in the range of 2 GHz it is only $3\mu s$. For delays smaller than $10\mu s$ the insertion loss could be smaller than 10 dB. Spurious signals suppression is around 40 dB. Delay lines are used in differential and poly phase differential demodulators for PSK digital signals. They are also used in videophone system processing in a so-called Hadamard's transformer. SAW delay lines have found very versatile applications in radar systems. They are used for signal sorting and signal processing in detection of moving targets. In pseudo-coherent mobile radars, delay lines (due to their small weight) are used for detection of slowly moving targets with clatter. Delay lines of variable delays are also used in radar systems. Delay lines are also used as vital parts of oscillators in satellite communications, coherent and pseudo-coherent radar systems, digital radio systems, Doppler radars, converters and video recorders. The characteristics of the oscillators are: power from 10mW to 100mW, frequency of 100 to 2000MHz, long term stability $2x10^{-5}$ per year, temperature stability $\pm$4ppm (ST quartz) in the temperature range of 10 to 40^{o}C. The actual size of one delay line is presented in Fig.7 [41].

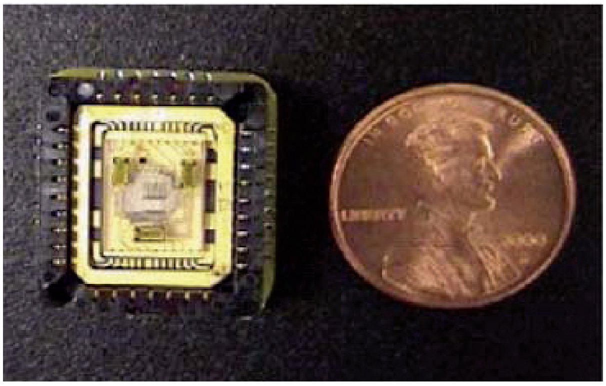

Figure 7. Four-channel SAW delay line packed in a leadless chip carrier [41]

The use of dispersive delay lines in pulse compression radars improves the signal to noise ratio and resolution with lower transmitter's peak power. In Fig. 8 the ALCOR RAC processor, which is also used in pulse compression radars, is shown [42]. This device replaced the entire seven-rack processor previously used.

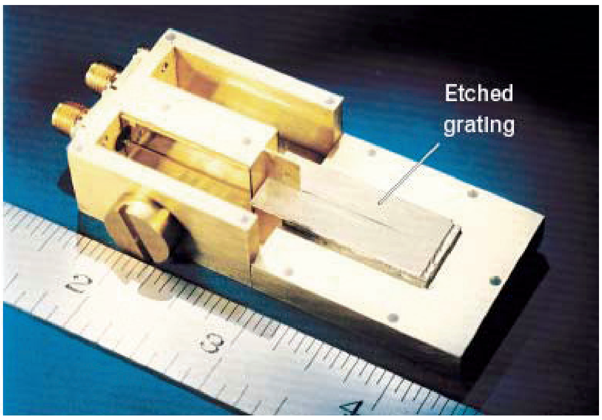

Figure 8. The ALCOR RAC processor [42].

Two dispersive delay lines with complementary delay characteristics can form the delay line with continually variable delay, which is widely used in simulation of moving targets. The characteristics of dispersive delay lines are: passband B up to 1 GHz, dispersion T up to 50 μs, TB product up to 500, and insertion loss up to 40 dB. SAW filters matched to bipolar PSK modulation are used in spread spectrum systems.

Among the producers of SAW devices there are very well-known companies such as: Andersen Laboratories, Murata, Siemens, Boston Electronic Corp, Alcatel, Thompson CSF, Sandia National Lab., Air Gate Technology and Com Dev SAW Products.

Conclusion

Surface acoustic wave devices are widely used in modern communications and signal processing systems in the VHF/UHF range. A wide variety of response functions can be obtained and the design is relatively straightforward. Device performance can match the required specifications very closely, even in the cases where they can hardly be achieved by other techniques. In some cases the use of SAW device has no alternative. The main advantages of SAW devices can be summarized as follows:

- versatile response function obtainable with little or no trimming necessary,
- design is straightforward,
- straightforward fabrication compatible with IC technology,
- good repeatability,
- small size and weight,
- passive (except for programmable filters),
- good dynamic range (80 dB),
- good temperature stability and
- radiation resistance.

Because of all these qualities SAW devices became vital parts of modern communication systems in the VHF and UHF range and it is expected that they are going to be even more used in the future.

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Elementi sa površinskim akustičkim talasom u telekomunikacijama

U radu je dat pregled principa rada i analize transverzalnih filtara sa površinskim akustičkim talasom (PAT). Prikazani su načini projektovanja različitih tipova ovih filtara kao što su propusnici opsega, linije za kašnjenje i disperzivne linije za kašnjenje, kao i mogućnosti i široka i raznovrsna primena ovih elemenata u telekomunikacijama.

Ključne reči: **PAT element, transferzalni filtar, PAT filtar, RAC filtar, linija za kašnjenje, telekomunikacije.**

Элементы с поверхностной акустической волной в телекоммуникациях

В настоящей работе пересмотрен принцип работы и анализа трансверзальных (поперечных) фильтров с поверхностной акустической волной (ПАВ). Здесь тоже показаны способы проектирования различных типов этих фильтров в роде пропускников охватов, линиии для опаздывания и дисперссивной линии для опаздывания, а в том роде и возможности и широкое и разнородное применение этих элементов в телекоммуникациях.

Ключевые слова: ПАВ элемент, трансверзальный фильтр, ПАВ фильтр, РАЦ фильтр, линия для опаздывания, телекоммуникации.

Eléments avec l'onde acoustique superficielle dans les télécommunications

Ce papier contient un aperçu sur les principes du fonctionnement et l'analyse des filtres transversaux avec l'onde acoustique superficielle (SAW). On a présenté les façons servant à dessiner les différents types de ces filtres tels que les filtres passe-bande, les lignes à retard et les lignes dispersives à retard ainsi que les capacités de ces éléments et leur vaste application dans les télécommunications.

Mots clés: **élément SAW, filtre transversal, filtre SAW , filtre RAC, ligne à retard, télécommunications.**