Design of SAW Expander and Compressor on $LiTaO_3$ for a TCDMA Spread Spectrum System

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***Abstract*—We report on the design and performance of surface-acoustic wave (SAW) minimum shift keying (MSK) tapped delay lines using pseudonoise code sequences with a length of 128 chips. As a substrate, X112°rotY-$LiTaO_3$ has been used due to the system requirements of a given CDMA/TDMA (TCDMA) radio communication system. System IF frequency, bandwidth of the major lobe, and integration time of the SAW devices were, respectively, 360 MHz, 63.5 MHz, and 3 μs. We used SAW tapped delay lines employing nonweighted as well as cosine-weighted input interdigital transducers incorporating split-fingers. We designed both expander as well as compressor filters attaining very similar experimental results. We found insertion loss values down to 16 dB and amplitude ripples of less than 2 dB. The close-in selectivity was 28 dB.**

***Index Terms*— Spread spectrum communication, surface-acoustic waves, tapped delay lines, TCDMA.**

I. Introduction

RADIO frequency (RF) consumer communications enjoy a tremendous growth due to the many upcoming wireless personal communicator applications in areas such as local area networks (LAN's), cordless telephones, communications with robots, telecontrol, security, data carrier, and communications in home, office, and factories. As RF applications expand, its advantages for local and small zone communications become more widely appreciated. One of the key technologies of RF consumer communications is thought to be the spread spectrum technique [1], [2] which has its origin in the military arena with a flurry of developments during and following World War II. Spread spectrum became the norm for military signalling since it reduces the friendly communicator's detectability and combats the enemy-introduced interference. Because of its inherent wideband transmission and the occurring processing gain, spread spectrum communication shows also an excellent performance against multipath phenomena and makes it possible to transmit signals along noisy channels with a high degree of signal security.

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With the change of the current world political situation, wireless spread spectrum communications have been allowed for consumer use on a number of industrial, scientific, and medical (ISM) frequency bands [3]. Thus, driven by the immense progress of communications devices, in the mid-1980's research groups began developing wireless spread spectrum demonstrators shifting spread spectrum from military to commercial applications. In the United States and in Japan, spread spectrum now is in practical use, e.g., in wireless LAN products. The ongoing trend toward spread spectrum is due to the demand for user privacy, low-power, unlicensed communication devices, and also inexpensiveness of systems.

In direct-sequence (DS) spread spectrum, in which fast pseudonoise (PN) codes are used for channel separation, RF energy is spread across a wide frequency band by replacing each data bit by a number of chips, i.e., multiple sub-bits, that occupy the same time interval. The more the signal is spread the lower the interference threat to or from other radios using the same frequency band. For that reason, both the United States and Japan insist on a minimum processing gain of 10 dB. The upper limit of processing gain is mainly determined by the available RF bandwidth.

Among feasible encoding and decoding techniques necessary in any spread spectrum system [4] is (analog) surface-acoustic wave (SAW) code generation and matched filtering to despread the received information signal [5]. In the latter case, the receiver has not only to despread and demodulate the local PN code but must correlate the spread signal to reconstruct its original content. Using SAW matched filters [6]–[8], the correlation can be carried out asynchronously, and the front-end hardware can be implemented simply and compactly. SAW matched filters show easily moderate correlation gain values in the order of 20–23 dB which cannot be met by digital matched filter implementations. Both the (programmable) SAW convolver [9], [10] and the (fixed-code) SAW tapped delay line (TDL) [11], [10] approach as matched filter are feasible. The TDL approach is in particular applicable to, e.g., the mobile stations of a mobile radio system because it is not necessary for the mobile stations to know the spreading codes of other mobile users.

In [12] and [13], a hybrid CDMA/TDMA system proposal (TCDMA) based on SAW encoding and decoding techniques has been worked out which is especially useful for communication systems with small delay spreads such as indoor and satellite communication systems. In what follows, we describe

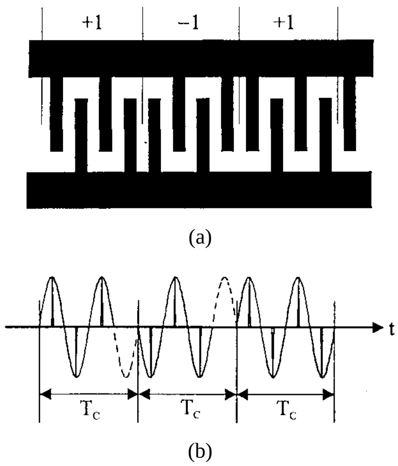


Fig. 1. (a) Phase-coded IDT for BPSK modulation and (b) BPSK signal.

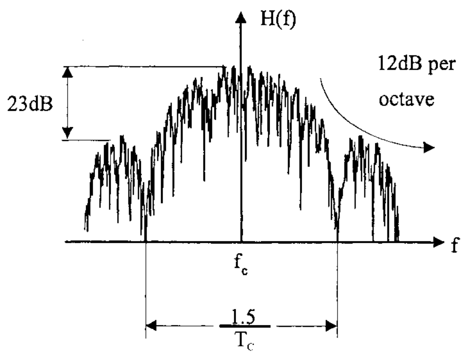


Fig. 2. Simulated power spectrum of MSK-modulated PN sequence with 128 chips.

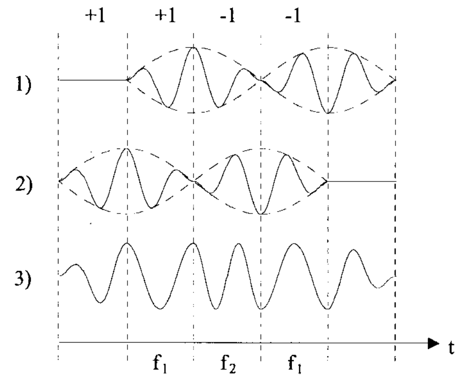


Fig. 3. Construction of an MSK signal (example).

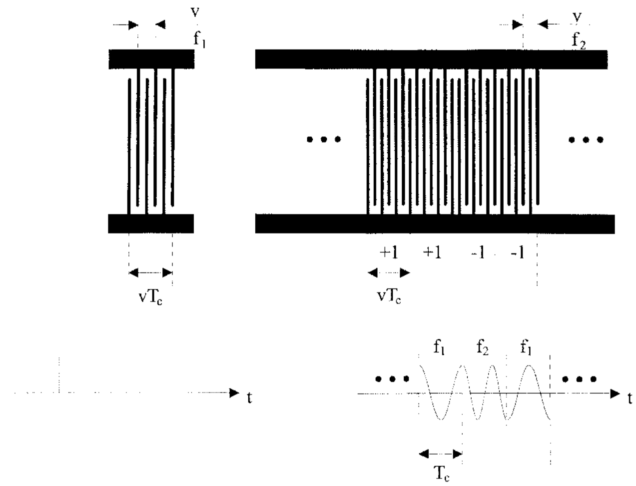


Fig. 4. SAW TDL using nonweighted input IDT.

minimum shift keying (MSK) xTDL's which are particularly designed to be applied in such a TCDMA system, e.g., by implementing selected code sequences.

II. SAW MSK Tapped Delay Lines

The SAW TDL is basically a linear transversal filter incorporating an input interdigital transducer (IDT) and an output IDT, one of which being phase-coded like the one shown in Fig. 1 for binary phase shift keying (BPSK) modulation. The chip-defining reversal of the waveform cycles is simply achieved by an appropriate polarity reversal of the IDT fingers. Instead of BPSK modulation which exhibits a theoretical sidelobe suppression of only 13 dB, we use MSK modulation. Fig. 2 gives the simulated power spectrum of an MSK-encoded PN sequence with a length of 128 chips. In comparison to BPSK, on the credit side of MSK are a 10-dB higher sidelobe suppression and 6-dB higher fall-off. The penalty is a somewhat smaller null-to-null bandwidth of $1.5/T_c$ with MSK compared to $2/T_c$ with BPSK (T_c: chip time), a fact which, however, is not a big issue in our application since the system bandwidth is greater than the coherence bandwidth of the radio fading channel which is typically in the order of 30–40 MHz.

The MSK condition represents the minimum frequency difference that will enable the 1-b and 0-b modulation excursions of the coded transmission to be separately correlated and detected. The MSK waveform has continous phase excursions going from frequency f_1 to f_2 with

$$f_{1,2} = f_c \pm \frac{1}{4T_c} \tag{1}$$

where f_c is the center (IF) frequency. The chip time T_c is determined by the reciprocal product of the number of chips per message bit N_c and the digital message bit rate R_b. As is seen in Fig. 3, an MSK signal may be constructed out of the superposition of an evenly modulated waveform cycle (curve 1) and an oddly modulated waveform cycle (curve 2). The resulting transmission (curve 3) is then in the form of contigous pulses at one of the two frequencies f_1 and f_2.

The SAW TDL implementation is achieved in one of two ways, with the same end result. Fig. 4 illustrates MSK-encoding using a nonweighted input IDT at synchronous frequency f_1 and a phase-coded output IDT at synchronous frequency f_2. The operation of this structure is quite obvious and yields the desired MSK signal.

In the alternative method illustrated in Fig. 5, the input IDT has sine function-overlap weighted fingers at center frequency f_c while the phase-coded output IDT is merely a broad-band receiver. To understand this, consider that the normalized impulse response of the input IDT is required to take the form

$$h(t) = \begin{cases} \sin(2\pi f_c t)\sin\left(\frac{\pi t}{2T_c}\right), & \text{for } 0 < t < T_c \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

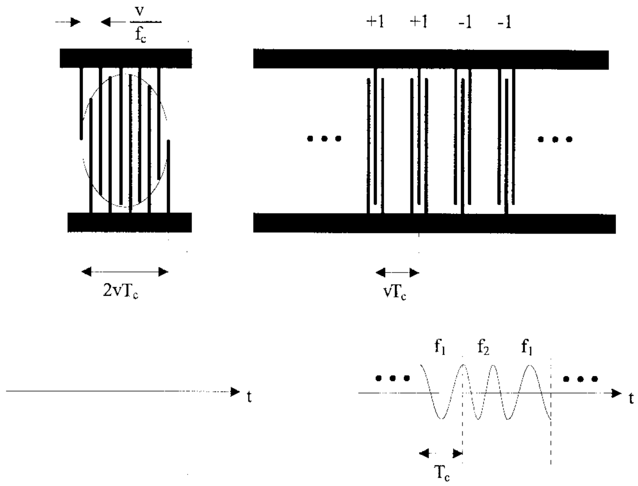


Fig. 5. SAW TDL using sine-apodized input IDT.

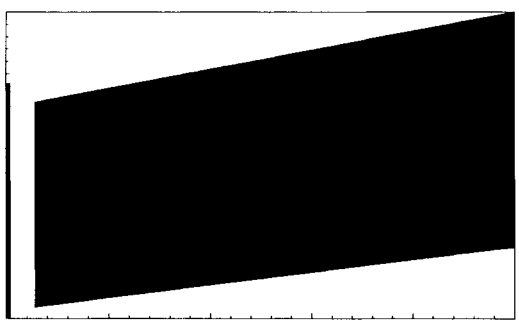


Fig. 6. TDL structure with tilted and overlap-weighted phase-coded output IDT.

The second sine function incorporates the weighting pattern of the input IDT. An expansion of (2) based on $\sin\alpha\sin\beta = 1/2[\cos(\alpha-\beta) - \cos(\alpha+\beta)]$ results in

$$h(t) = \begin{cases} \frac{1}{2}[\cos(2\pi f_1 t) - \cos(2\pi f_2 t)], & \text{for } 0 < t < T_c \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

with $f_{1,2}$ given by (1). Equation (3) contains both f_1 and f_2 instead of one or the other. This first sight dilemma can easily be overcome by selecting the IDT length to be an odd number of half cycles in length at center frequency f_c. In our IDT design, we use an IDT length of $2T_c$. With an even number of fingers of the input IDT, we obtain then the result that the frequency of the output signal will be again f_1 or f_2 depending on whether the consecutive input impulses have the same or opposite voltage polarity.

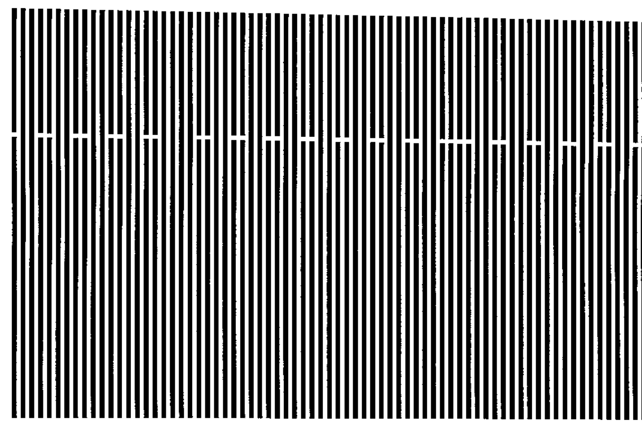
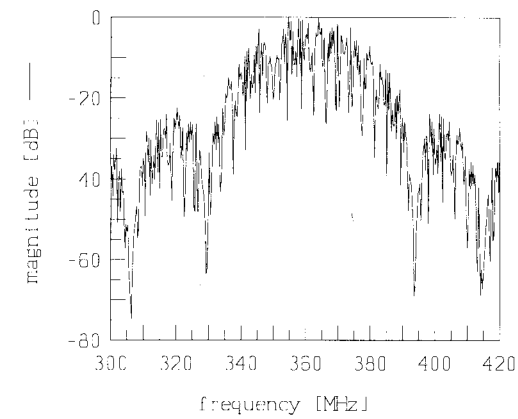
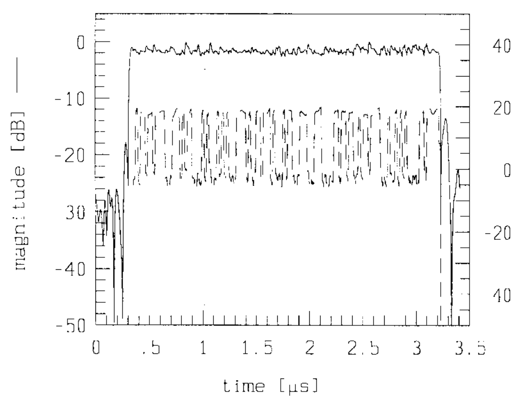


Fig. 7. Section of phase-coded output IDT (16 cycles per chip).



(a)



(b)

Fig. 8. Computed behavior of a 360-MHz TDL using nonweighted input IDT: (a) frequency response and (b) magnitude (—–) and relative instantaneous frequency (- - -) of impulse response.

III. SAW Design and Simulation

The present paper arose from a requirement of TDL's processing 128-chip Gold codes with an integration time of 3 μs and a bandwidth greater than 50 MHz. The IF frequency of the 2.45-GHz TCDMA indoor communication system was chosen to be 360 MHz, i.e., the SAW center frequency f_c is 360 MHz. Broad-band matching to a 50-Ω environment, temperature stability, and insertion loss considerations [14], [15] led to the substrate material X112°rotY-$LiTaO_3$ (a certain crystal cut of lithium tantalate) instead of quartz or lithium niobate crystal cuts. Quartz substrates avoid to a relatively high extent phase errors due to temperature changes, however, with a penalty in increased insertion loss. For example, using quartz as a substrate, our simulations yielded an unmatched insertion loss of more than 50 dB.

The required bit rate of $R_b = 333$ kb/s yields chip times T_c around 23 ns, i.e., at $f_c = 360$ MHz we have 16 cycles per chip. IDT's employing split-fingers with $\lambda/8$ strip width (λ: microacoustic wavelength) and dummy electrodes have been used to suppress spurious finger reflections and stop

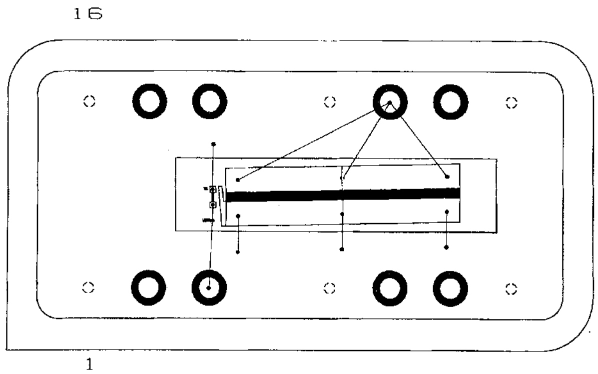


Fig. 9. Test chip (triple bonding).

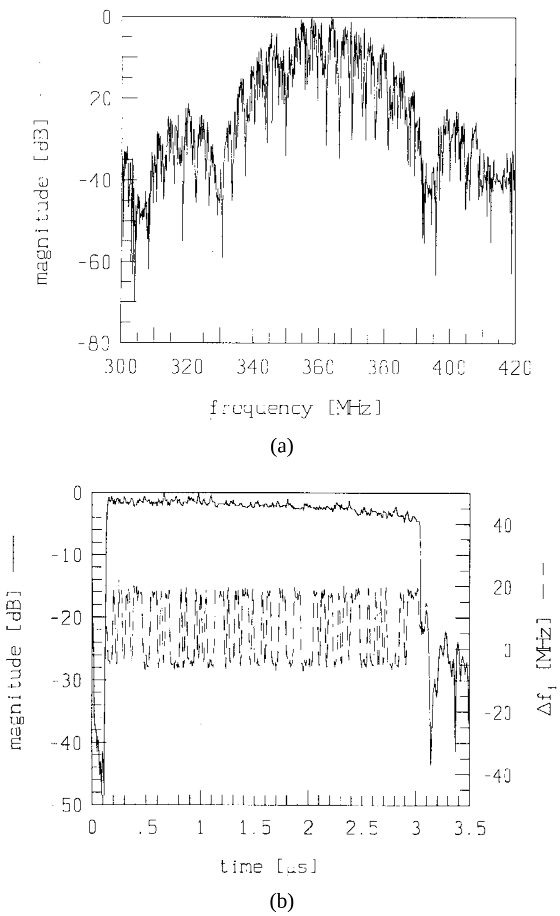


Fig. 10. Experimental behavior of an unmatched 360-MHz TDL using nonweighted input IDT. (a) Frequency response and (b) magnitude (—) and relative instantaneous frequency (- - -) of impulse response.

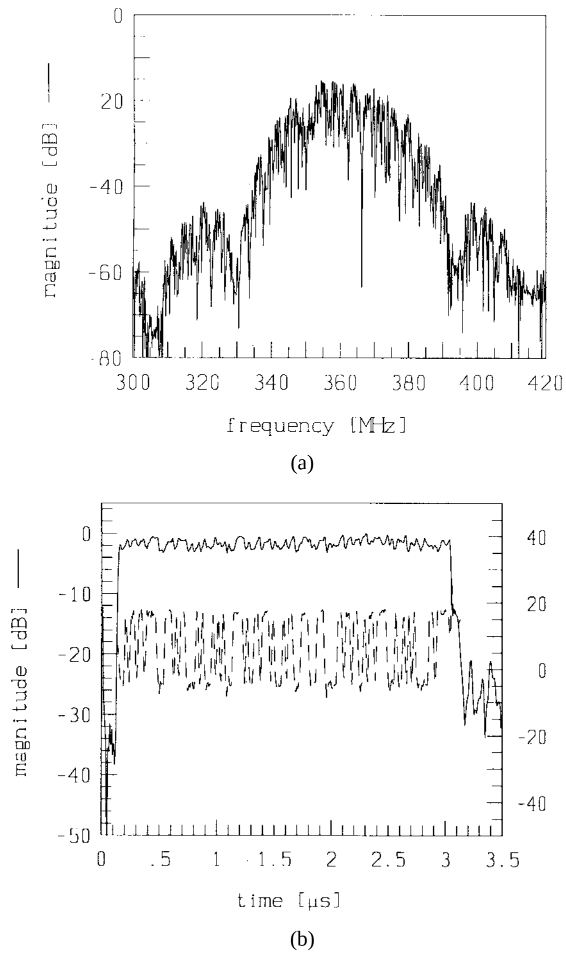


Fig. 11. Experimental behavior of a matched 360-MHz TDL using non-weighted input IDT: (a) frequency response and (b) magnitude (—) and relative instantaneous frequency (- - -) of impulse response.

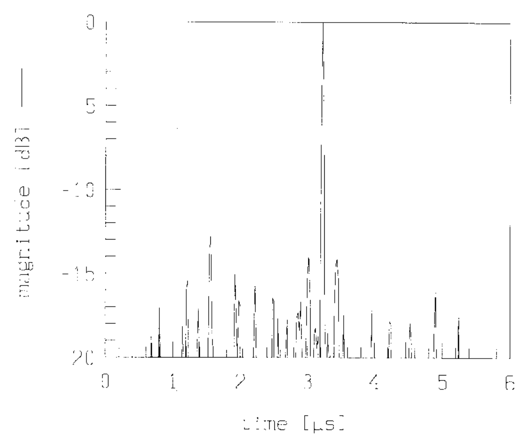


Fig. 12. Experimental correlation of SAW expander-compressor test system.

band harmonics which otherwise would occur at such a high number of IDT fingers. The SAW devices are fabricated using conventional optical lithography technology. Having a phase velocity of the SAW propagation of $v = 3285.5$ m/s, we obtain microacoustic wavelengths in the order of 9 μm, i.e., $\lambda/8 \approx 1.1$ μm. Tradeoffs based on second-order phenomena such as direct electromagnetic feedthrough between the TDL IDT's, wave propagation losses and diffraction, Ohmic losses, reflections, etc., [16] have been compromised for by using IDT apertures and inter-IDT distances in the order of 80λ, and a metallization height (aluminum) of 150 nm.

The SAW design is based on simulations which were carried out using traditional impulse response modeling, P-matrix modeling [17], and angular spectrum of waves analysis [18]. First, the principal geometrical data of the TDL's were derived based on signal-theory guidelines and network-theory (P-matrix) computations. Finally, angular spectrum of waves analysis has been used to compensate for the beam steering angle of 1.11° and wave propagation losses due to diffraction

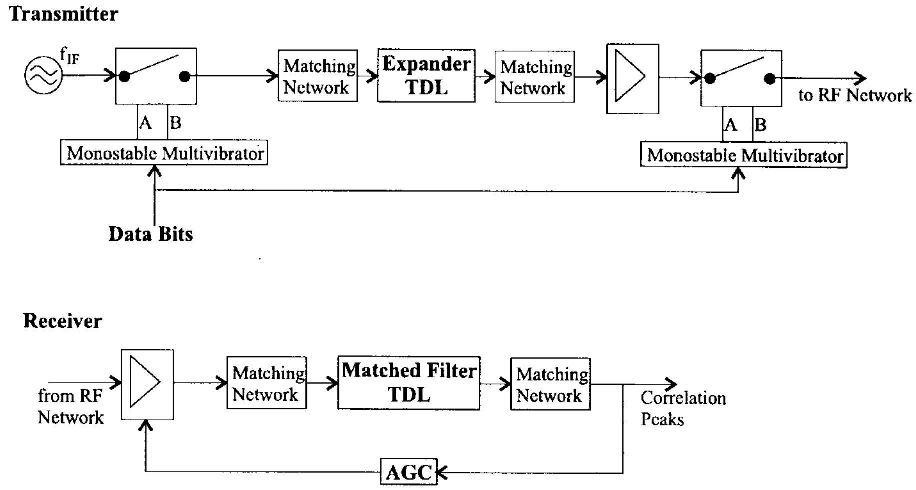


Fig. 13. Test setup.

and attenuation by tilting the axis and linearly weighting the finger overlap of the phase-coded output IDT in a manner which is schematically illustrated (not to scale) in Fig. 6. To detail the split-finger structure, a section of the 4064-fingers IDT is sketched in Fig. 7 showing, e.g., that 16 cycles per chip have been used. The SAW design procedure is outlined in [19] and detailed in [20] and [21]. A typical simulation result is given in Fig. 8. The time-domain response shows a very flat and low-ripple behavior, and the time dependence of the relative instantaneous frequency Δf_i which is the differential of the time-domain phase illustrates the implemented code.

IV. Experimental Results

Several TDL structures (encoding and decoding ones) employing both nonweighted and sine-apodized input IDT's were simulated before the masks were designed. Fig. 9 shows a test chip mounted in a DIP14 package. Three bond wires have been used for connecting the bus bars in order to reduce the Ohmic losses due to the bus bars.

Since our various design approaches yield basically similar experimental results, we will discuss in detail only the performance of an encoding device employing a nonweighted input IDT at f_1 and a phase-coded output IDT at f_2. Fig. 10 gives the experimental results of such a TDL. The unmatched insertion loss in this case is 36 dB. The input IDT's have high impedances, whereas the output IDT's have low impedances. This is due to the fact that they have, respectively, few and many fingers. Therefore, in practice, broad-band matching is an issue to be addressed thoroughly. We matched the TDL's successfully over bandwidths greater than 60 MHz to insertion loss values as low as 15.5 dB which is seen in Fig. 11. Amplitude ripple and close-in selectivity are 1 and 28 dB, respectively. Fig. 12 gives the experimental time-domain correlation result of a test system incorporating an expander and a compressor as is shown in Fig. 13. We achieved a sidelobe suppression of the communication system of nearly 13 dB.

All the measurements shown above have been made at an environmental temperature of 20 °C. Let us now discuss the temperature stability of the TDL's. In any SAW device, temperature effects cause the response to vary with temperature since temperature changes affect both the SAW velocity and the substrate size, resulting in phase errors. These errors affect the sidelobe amplitudes as well as the correlation peak, though the sidelobe changes are not generally significant if the reduction of the peak is acceptable. From the temperature stability point of view, $LiTaO_3$ lies between quartz, which is relatively stable, and $LiNbO_3$. Fig. 14 gives the experimental temperature behavior of the TDL discussed above in terms of sidelobe level versus temperature. As is seen, at room temperature we have a maximum of sidelobe suppression of about 13 dB which drops off to lower as well as to higher temperatures. Outside the range between −20 °C and +60 °C, the processing gain completely vanishes. In a practical spread spectrum receiver, this temperature dependence has to be compensated for, e.g., by properly controling the frequency of the local oscillator using a phase-locked loop (PLL) configuration as is demonstrated in [15].

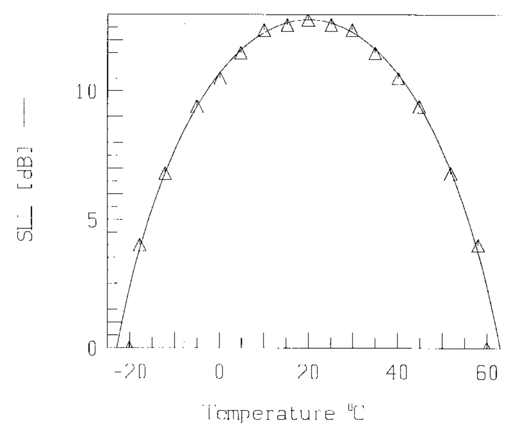


Fig. 14. Experimental side lobe suppression in dependence of temperature: (—) theory, (△) measurement.

V. Conclusion

The present paper demonstrates a good performance of moderate processing gain (and thus low-cost) SAW tapped delay lines fabricated on $LiTaO_3$ for broad-band spread spectrum applications. The devices have been designed for use in a special TCDMA indoor mobile radio system demonstrator using selected Gold codes for down- and uplink and m-sequences for the synchronization channel (which is only foreseen in the downlink). We expect that in the decade ahead such SAW devices will play an important role in radio-based spread spectrum communications.

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He became Professor of Electronics at TU in 1974 and worked in microwave measurements of the acoustoelectric effect, where he invented the acoustic charge transport devices in 1971. Since 1976, his group has been active in SAW research and spread spectrum applications. Since 1981, there has been a close cooperation with Siemens Corporate Research Laboratories, Munich, Germany, which led to a leading position in SAW design and fabrication, which made possible the implementation of SAW devices for new applications in Vienna. Among these is the production of the first spread spectrum systems in Austrian industry. He is the author and co-author of about 200 publications and one book and holds several patents and two scientific prizes.

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