Design, Fabrication, and Application of Precise SAW Delay Lines Used in an FMCW Radar System

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***Abstract*—An inexpensive frequency-modulated continuous-wave (FMCW) radar system is presented in this paper, which, nevertheless, meets all industrial requirements. The FMCW radar uses a low-cost nonlinear voltage-controlled oscillator (VCO), operating at an IF of 2.45 GHz to generate the frequency modulation of the radar system. This VCO signal is applied twice, first to generate the radar transmitter signal at 24 GHz, and then it is fed to a surface acoustic wave (SAW) delay line. The SAW delay line generates a fixed delay time, which corresponds with a fixed radar distance. Thus, all systematic nonlinearities and stochastic phase errors of the FMCW system can be monitored and, afterwards, can be compensated for in real time. This linearization technique leads to a significant enhancement in dynamic range for a FMCW radar system. For this FMCW system, SAW delay lines with a linear phase characteristic have been designed using a linear optimization program. The delay line consists of two chirped and weighted interdigital transducers. For high volume, low-cost, and high-yield production of the required SAW structures, with linewidths down to 0.3 μm, technological improvements had to be achieved, especially in photolithography. Based on these design and fabrication techniques, delay lines at 2.45 GHz operating at the fundamental and third harmonic with bandwidths up to 800 MHz have been realized.**

***Index Terms*—Chirp, FMCW radar, linearization, photolithography, SAW delay line, tank level gauge, 0.3-μm linewidth, weighted IDTs.**

I. INTRODUCTION

WITHIN the last decade, great and important progress in surface acoustic wave (SAW) device specifications was made and a variety of innovative applications were acquired, mainly driven by the booming wireless products business. These developments were based on new SAW design and optimization algorithms, on other technological improvements, as well as on novel circuit concepts. In this paper, a new and innovative application for SAW devices will be presented. The SAW devices serve as a fixed electrical delay line for the linearization of frequency-modulated continuous-wave (FMCW) radar.

The goal of the engineering effort, which is reported in this paper, is to develop an inexpensive FMCW radar system, which nevertheless fulfills all industrial design specifications. Therefore, a low-cost, but nonlinear, voltage-controlled oscillator (VCO) operating at an IF of 2.45 GHz is used to generate the frequency modulation of the radar. The VCO signal is used twice, first for up-conversion with a stable local oscillator (LO) to generate the FMCW RF signal, and then it is fed to a SAW delay line. The SAW delay line generates a fixed delay time, which corresponds to a fixed radar distance. Thus, all nonlinearities of the FMCW system can be monitored and compensated for in real time. This linearization technique leads to a significant enhancement of the dynamic range of the FMCW sensor.

IF frequency was set at 2.45 GHz because, in that frequency range, many low-cost components are available, and also to lower the relative bandwidth of the SAW delay line because bandwidths up to 800 MHz, or even more, are needed.

Using a standard SAW technique with uniform sampled transducers would result in a high-insertion attenuation because the impedance of the interdigital transducers (IDTs) would obtain bad matching conditions. Furthermore, a lot of small taps would occur from the compensation procedure (leading to additional losses) because small taps are affected by strong diffraction effects. The insertion loss of filters with high relative bandwidth can be reduced using dispersive IDTs [1]. We, therefore, decided to realize the SAW delay line with two chirped and weighted IDTs.

In Section II, the design and optimization algorithm for SAW linear phase delay lines consisting of two chirped and weighted IDTs will be discussed. For high-volume, low-cost, and high-yield production of SAW structures with linewidths down to 0.3 μm, technological improvements in the SAW production technique had to be achieved, especially in photolithography. Section III gives a short overview of these fabrication challenges. Section IV discuss the SAW delay lines, which were realized based on these design and fabrication techniques. Several examples of filters with different bandwidths operating at the fundamental and third harmonics are discussed. These delay lines, operating at the fundamental harmonics, were manufactured on the rotated cut of $LiNbO_3$ and had normal fingers only. The height of metallization was chosen for minimum reflections. The minimum linewidth necessary was 0.3 μm. Delay lines, operating at the third harmonic, were manufactured on the YZ cut of $LiNbO_3$ and had split fingers for canceling reflections. In this design, minimum linewidths of approximately 0.45 μm had to be realized. Comparisons of the measured and

Manuscript received October 18, 2000; revised January 15, 2001.

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Publisher Item Identifier S 0018-9480(01)02904-0.

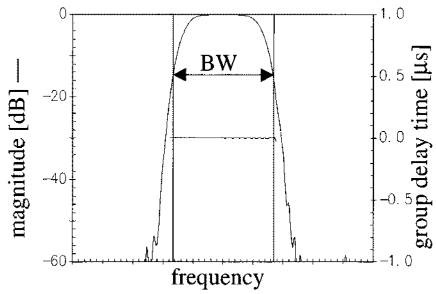


Fig. 1. Desired frequency response $H(f)$ of the filter. Three different bandwidths BW of 400, 600, and 800 MHz were investigated.

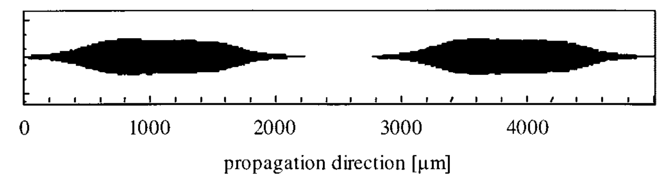


Fig. 2. Geometry of one filter. The meander line through the active taps of both IDTs is depicted.

calculated frequency responses of these delay lines are given in Section IV.

Section V explains the FMCW radar system and the algorithm for compensation of the VCO nonlinearities in detail. A brief conclusion then follows in Section VI.

II. Design of the SAW Delay Line

Many excellent design techniques are available for filters with uniformly sampled IDTs. Optimization programs like linear programming [2], [3], the Remez exchange algorithm [4], and the quasi-Newton method [5] can be used for the linear design. Together with compensation procedures [6]–[9] and accurate analysis [2], [10]–[14], it is possible to design filters with accurately shaped passband and desired stopband rejection.

Similar design tools are not available for filters with nonequidistantly sampled IDTs. Usually the finite impulse response (FIR) design of a chirped IDT starts with the waveform design in the time domain [15]–[18], but few papers deal with the design of filters with a low time-bandwidth product [19]–[21]. Fulfilling frequency —domain specifications is an iterative process. To achieve a precisely shaped passband and to meet the stringent specifications in frequency domain requires skilfull design. Therefore, we used a two-step procedure for the linear design of nonuniformly sampled IDTs.

The desired frequency response $H(f)$ of the filter was designed first. Any standard design procedure for designing transversal SAW filters can be used, e.g., the linear programming technique [2], [22]. Amplitude and phase characteristics can be chosen almost arbitrarily. In our design, we chose a frequency response for which amplitude response is flat over almost the entire target bandwidth BW of the filter (see Fig. 1).

In the next step, the frequency response has be split into two IDTs. Standard solutions result in filters consisting of an apodized and uniform transducer, with one or both transducers being dispersive. In this configuration, Fresnel ripple originating from the uniform transducer leads to problems [10], therefore, the apodized transducer has to compensate for this Fresnel ripple.

To overcome this situation, it is advantageous to use two dispersive and amplitude weighted transducers. There are, however, some drawbacks. The linear design is difficult because the transfer function of the filter is not even in first order equal to the product of the transfer functions of both transducers. Compared to configurations using only one uniform transducer, second-order effects, e.g., diffraction, become more severe. In order to compensate for these second-order effects, precise simulation tools for all relevant second-order effects, e.g., diffraction, reflection, refraction, are required.

The splitting of the frequency response into two weighted IDTs is done using the square-root method [22]. This is not optimal; however, deviations can be compensated for in the compensation procedure for second-order effects. We then multiplied appropriate phases (chirp functions), which cancel each other (unklar!!) to both frequency responses of the IDTs. The chirp rate was chosen to get a effective matching condition for the IDTs. After transforming into the time domain, we apply a nonlinear sampling method to both time functions, resulting in initial guesses for the two IDTs of the delay line [23], [24].

Next, the nonlinear phase was multiplied to this frequency response and the IDT with the resulting time response was synthesized by a nonequidistant sampling method [23]. This sampling method enables an in-band compensation procedure for second-order effects in delay lines with two amplitude weighted and almost linear chirped IDTs.

In order to design a filter operating at the third harmonic, we initially attempted to design the filter at the fundamental and compensate for the third harmonic. However, aliasing generated an undesirable ripple in the passband of the third harmonic. Since aliasing affects the first and third harmonic response differently, the compensation procedure could not converge. Therefore, a second approach was chosen for the design of the dispersive IDTs operating at the third harmonic. We designed the filter at its nominal frequency and instead of taking every tap, only every third active tap was realized. For IDTs operating at even higher harmonics, every fifth, seventh, . . ., active tap may be selected.

The frequency response of this filter—computed using the impulse model—was already the desired one. To simulate second-order effects, an extended angular spectrum of a straight crested-wave model [10], [12], [13] was used. In case of deviations from the desired frequency response, we modified the two frequency responses determining the two IDTs. The number of necessary iterations depends on the specifications of the dispersive delay line. If the aperture, chirp rate of the IDTs, and distance in between are chosen in an adequate manner, 5–10 iterations of the compensation procedure are sufficient. Fig. 2 shows the final geometry of one of the filters. The meander line through the active taps of both IDTs is depicted in an isotropic chart.

For the substrate of the delay lines, $LiNbO_3$ was chosen. The delay lines operating at the third harmonic were fabricated on

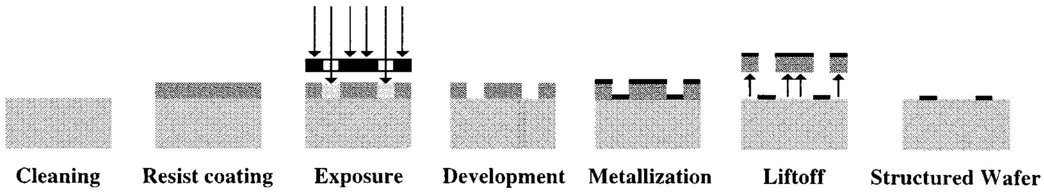


Fig. 3. Process flow of the SAW device fabrication.

the YZ cut. For the delay lines operating at the fundamental harmonic, only normal fingers could be used. To overcome problems with reflections, the rotated cut of $LiNbO_3$ and an adequate metallization thickness were chosen [33]. The test devices were fabricated using a liftoff process, projection printing, and an I-line wafer stepper. Linewidths down to 0.3 μm had to be achieved. The metallization is with aluminum.

III. Fabrication of the Devices

SAW devices operating at 2.45 GHz in the fundamental harmonic require a submicrometer patterning process [25]. SAW devices with submicrometer patterns have been fabricated in recent years using different exposure systems. E-beam [26], X-ray [27], and ion projection [28] all make possible linewidths close to 0.1 μm and fundamental frequencies up to 10 GHz. Due to the experimental state of X-ray and ion projection techniques and the long exposure times needed using E-beam writing, these methods are unsuited for mass production. Therefore, to meet the requirements for mass production, we greatly improved the standard I-line lithography fabrication process [29].

Since the center frequency of SAW devices is directly related to the linewidth of the transducer electrodes and to the velocity of the SAW modes propagating along the surface of the piezoelectric substrate, linewidths of less than 0.4 μm are necessary. The submicrometer patterning process [30] must have high reproducibility to be applicable to SAW devices. Optical projection printing in conjugation with a liftoff process using a single resist layer technique can be used for high volume, low-cost, and high-yield production. Most important for a successful fabrication of the delay lines is the appropriate configuration of the exposure tool, a Nikon I-line wafer stepper (reduction ratio 5 : 1) with a variable numerical aperture (NA) up to 0.63. This high NA value and the exposure wavelength of 365 nm enable the resolution of 0.3-μm IDT patterns. The disadvantage of this combination is a small depth-of-focus (DOF), but this could be overcome by using off-axis illumination (OAI) techniques [31]. OAI is a powerful tool to increase the depth of focus, as well as the resolution, and it is applied to increase the contrast of line/space patterns. Near the resolution limit, OAI has strong effects and can extend the standard I-line lithography down to 0.3 μm. An adequate quadruple illumination of the reticle, optimized by aerial image simulation [32] for the given linewidth of 0.3 μm, has significantly improved the depth of focus.

To create liftoff patterns, a high resolution positive tones resist, e.g., THMR-iP3250, was exposed by the I-line wafer stepper and developed with TMAH developer solution. Deposits of layers from 25 nm up to 0.8 μm of aluminum with an accuracy of about 1% over the wafer were made using an electron-beam evaporation system. Liftoff was carried out by dissolving the remaining resist in N–methyl–pyrrolidone (Fig. 3). Fig. 4 shows a scanning electron microscopy (SEM) photograph of a part of the 0.3-μm IDT pattern made with the described manufacturing process. It demonstrates the high resolution and good edge quality of this liftoff process.

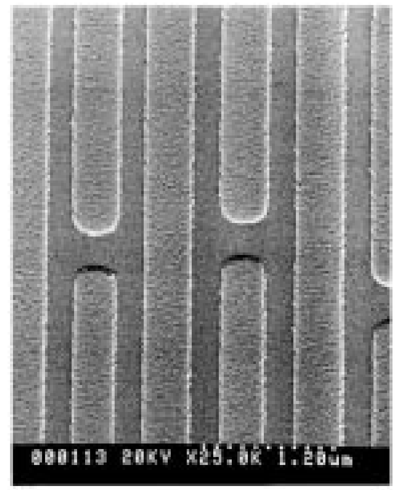


Fig. 4. SEM photograph of part of the IDT (0.6-μm periodicity and 0.4-μm linewidth).

To measure the devices, the wafers had to be diced and the single chips assembled in TO-39 and small SMD packages.

IV. Theoretical and Experimental Results

One problem of the experimental characterization of SAW devices at 2.45 GHz is electromagnetic feed-through. Our experimental data were obtained using a standard test socket. Compared to measurements on wafers or of devices soldered to a board, we had significant variations in feed-through. We tried devices incorporating a shielding pad between both IDTs (see Fig. 5), but this showed no improvement. We, therefore, decided to use an appropriate time gate for the presented measurements because, in the intended radar application (see Section V), the level of the feed-through is not critical.

The delay lines operating at the third harmonic were designed on the YZ cut of $LiNbO_3$. Three different bandwidths of 400, 600, and 800 MHz were investigated. The highest bandwidth is close to the obtainable maximum bandwidth of one third of the center frequency. The fingers at the low-frequency end of the IDTs become normal fingers for the highest frequencies and, therefore, strong reflections occur [see Fig. 6(a)]. In the time domain, two strong echoes before and after the main lobe of the impulse arise [see Fig. 6(b)]. Therefore, we produced only

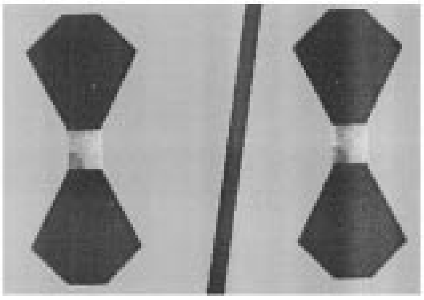
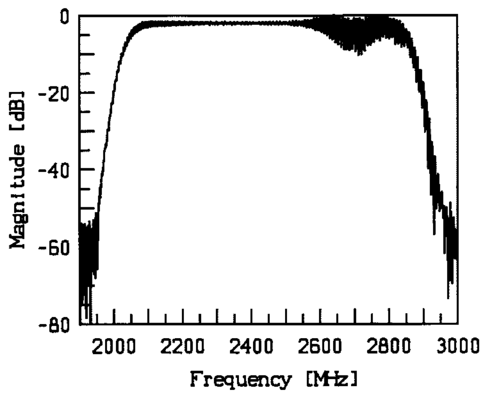
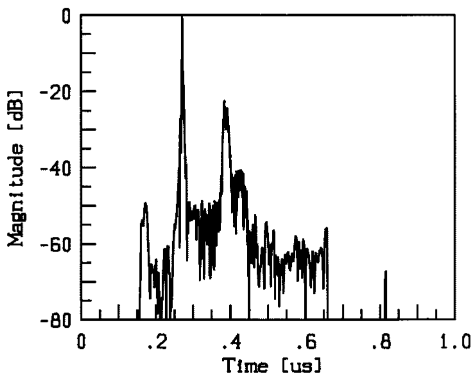


Fig. 5. Typical layout of the experimental devices incorporating a shielding pad between both IDTs to lower electromagnetic feed-through.



(a)



(b)

Fig. 6. (a) Simulated frequency response of a delay line at 2.45 GHz with a bandwidth of approximately 800 MHz. (b) Impulse response of the delay line with 800-MHz bandwidth.

the devices with a bandwidth of 400 and 600 MHz (Fig. 7). Such devices exhibit excellent passband characteristics and low group-delay distortions.

For dispersive split-finger IDTs operating at the fundamental frequency, finger widths of less than 0.16 μm are necessary. This is possible, but not with standard SAW manufacturing processes. Therefore, we decided to use normal fingers, which resulted in linewidths close to 0.3 μm. By using the YZ cut of $LiNbO_3$ and an appropriate metallization height [33], reflection-free IDTs were designed. As can be seen in Fig. 8, reflections within the passband are low. Further effort will be needed to be expended investigating the effects which are causing the tilt of the passband. An improved simulation program for normal fingers on the rotated cut of $LiNbO_3$ for high frequencies has to be developed and will be taken into account

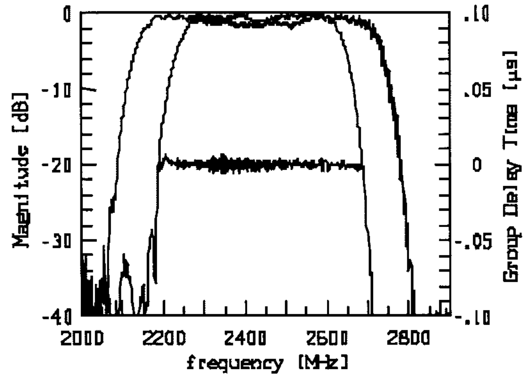


Fig. 7. Measured frequency responses of two delay lines at 2.45 GHz with bandwidths of 400 and 600 MHz, respectively.

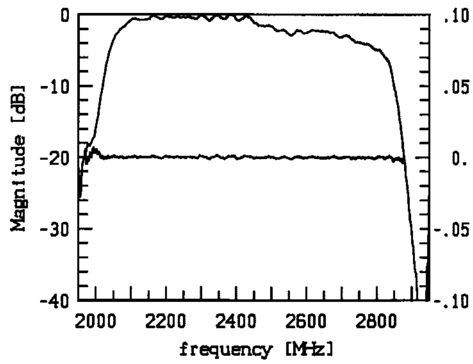


Fig. 8. Measured frequency response of the delay line operating at the fundamental harmonic.

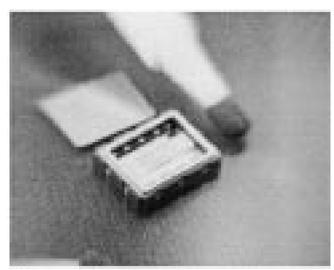


Fig. 9. Mounted SAW chip in a DCC6 housing.

in future designs. Nevertheless, the group delay linearity of this filter in its present form is excellent.

Fig. 9 shows the final SAW chip for radar application mounted in a DCC6 housing.

V. Application for Industrial Sensors

The process control industry needs to monitor the level of a wide range of different products stored in tanks throughout chemical and pharmaceutical plants, power plants, oil refineries, pulp, and paper and cement mills. Traditional level instruments (e.g., float gauges, capacitance probes, difference pressure transmitters) require a mechanical contact and, thus, have limitations arising from diverse process conditions (e.g., corrosive media and changes in density, pressure, dielectric constant, temperature).

Microwave technology has proven to be well suited for the determination of tank levels detection due to the noncontact

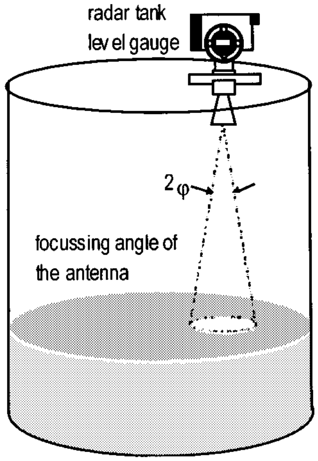


Fig. 10. Industrial radar tank level gauge.

sensing principle (see Fig. 10), its reliability in a wide measuring range and robustness against temperature, pressure, steam, and dust conditions [34]. The sales and market share of radar level gauges is increasing steadily. Most of today's systems operate at 5.8 or 10 GHz [35]. However, the next product generation of these products is expected to shift to 24-GHz technology [36]. Operating at higher frequencies, the level gauges will become smaller due to the reduced antenna dimensions, and easier to handle due to the sharper focusing of the radar beams. Operating at higher frequencies also leads to higher reliability and accuracy due to the higher gain and the larger allowed bandwidths.

Microwave applications require inexpensive, but very accurate sensor designs. Two major range-sensing principles are used in commercial radar level gauges: the pulse delay and FMCW principle. In the application as discussed here, the FMCW sensor principle is implemented because this offers cost-effective measurements of distance and speed. An FMCW radar sensor transmits a linear frequency modulated continuous wave and receives the corresponding echo from the reflection at the target. Due to the delay time, the received signal is frequency shifted according to the actually transmitted signal. The FMCW sensor obtains range information by a frequency/phase comparison between the received and actually transmitted signal. However, since the accuracy of conventional FMCW sensors is limited by the frequency linearity and the phase noise of the VCO [37], a linearizing algorithm equalizer has to be implemented in the FMCW radar transceiver.

In order to take advantage of the reported 2.45-GHz delay lines, we built a novel type of FMCW radar system with adaptive phase-error compensation. This approach is based on the idea that any phase errors can be eliminated by appropriate digital signal processing if the instantaneous phase of the transmitted microwave signal is monitored simultaneously during each frequency sweep. Fig. 11 shows the topology of the investigated millimeter-wave sensor system [38], which is comprised of a target path, as well as a reference path. The frequency is modulated using a 2.4-GHz VCO, whose frequency is shifted over a bandwidth of 500 MHz by the slope modulation voltage VCO_IN. This modulated 2.4-GHz signal is mixed to the radar transmitter frequency at 24 GHz with the help of a stabilized 21.7-GHz LO. After filtering (BP) and amplification (AMP), the transmitting (TX) signal is then feed to the antenna. The radar receiver uses Schottky diode mixer (*RX mixer*), which generates the target signal by homodyne conversion of the received signal with the actual transmitter signal.

The second part of the VCO signal is transferred to a miniaturized reference path, which also generates a delay time corresponding to about 100-m radar distance due to the use of the SAW delay line. The resulting reference signal serves as a basis for a phase compensation algorithm [39], which removes phase errors from the target signal according to the phase distortion measured within the SAW reference path. Fig. 12 illustrates the compensation algorithm. The phase errors due to a nonlinear frequency modulation comes into effect in both the target signal and reference signal. Furthermore, assuming only slowly varying modulation nonlinearities, the value of the occurring phase error will increase with increasing delay time. With the help of a nonequidistant sampling of the target signal at constant phase increments of the reference signal, all phase errors in the target signal are eliminated. If a phase increment of 180° is chosen, then the target signal is sampled at the zero crossings of the reference signal, as shown in Fig. 12 [40].

Fig. 13 illustrates the effect of phase errors on the fast Fourier transform (FFT) echo spectrum of a target at a distance of about 100 m. Due to these phase errors, the raw target echo [see Fig. 13(a)] is spread over a wide bandwidth. After phase error compensation, the same echo is compressed to a narrow peak [see Fig. 13(b)]. In the presented system, the described linearization technique is proven to significantly enhance the dynamic range of the FMCW sensor, particularly for very distant targets. Using this linearization concept, the new industrial radar tank level gauge "SITRANS LR" (see Fig. 14) has been introduced by Siemens, Karlsruhe, Germany, in 1999 [41] .

Now the performance of the radar is limited only by the parameters of the SAW reference—essentially, the constancy of the time delay—rather than by the properties of the microwave hardware. Synergy with other application opportunities for microwave sensors, such as automotive distance warning systems for example, will further reduce the manufacturing costs for this electronic device [42]. A greater improvement of the measurement accuracy is not required for most industrial uses. The discussed radar can even be approved by the Bureau of Standards for application in a level gauge. For this application, however, a careful choice of components and additional algorithms in the signal processing are required.

The use of SAW delay lines in high-precision industrial radars is, of course, only one example for the possible utilization of SAW delay lines. Many other applications, e.g., in communication systems, in systems for oscillator phase-noise measurement, or for calibration of radar units are feasible. For instance, in [43], a novel FMCW radar-based concept for precise measurement of the three-dimensional (3-D) position of an active backscatter transponder was recently presented. The employed 2.45-GHz radar units are very similar to the filling level system described above. However, for the 3-D position tracker, SAW devices are incorporated not only by the radar basestations, but also by the active backscatter transponder. The SAW used in this

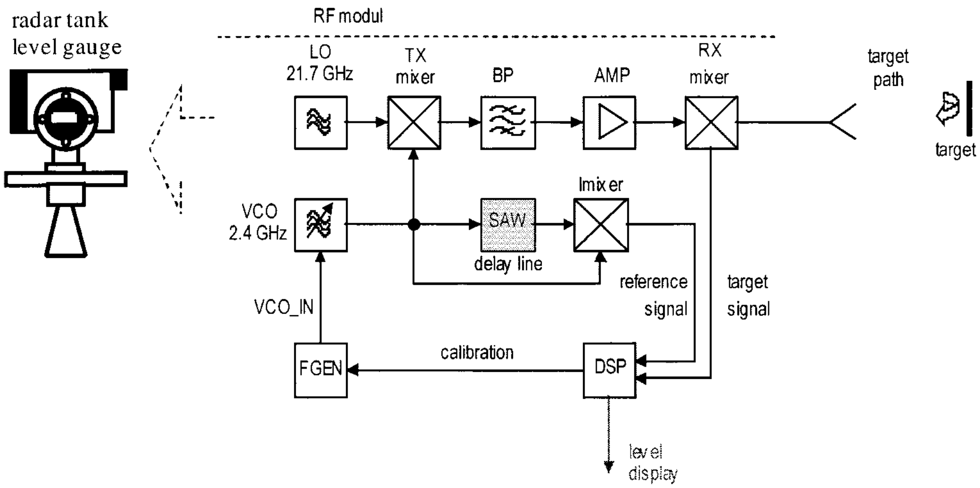


Fig. 11. FMCW radar sensor including the SAW reference. Phase-error compensation is based on digital signal processing.

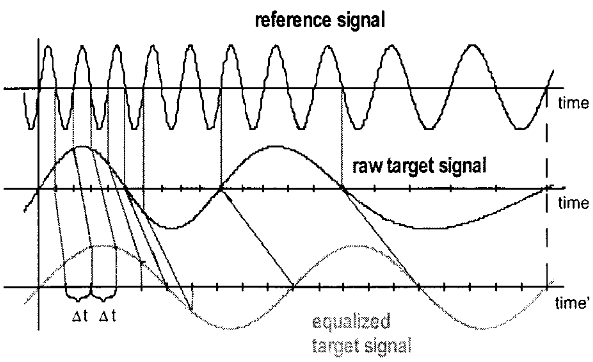


Fig. 12. Self-calibration of the radar transceiver using a nonequidistant sampling of the target signal.

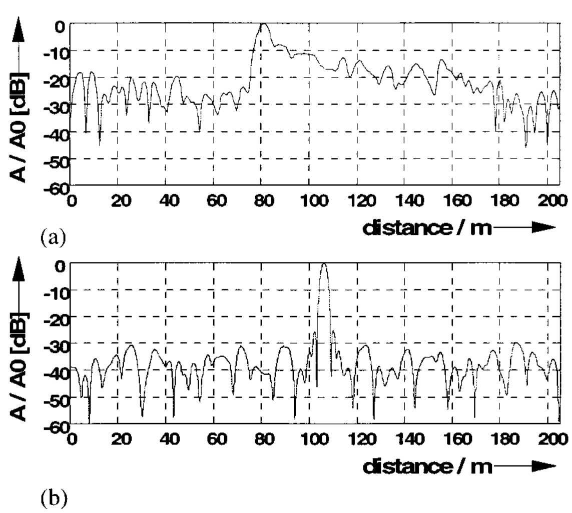


Fig. 13. (a) Measured target echo. (b) Same target echo after phase error compensation.

particular transponder is a special combination of resonator and delay line. This makes the sensor system completely self-calibrating and achieves more positioning precision in the submillimeter range.

Fig. 14. Siemens industrial radar tank level gauge "SITRANS LR."

VI. Conclusions

Accurate SAW delay lines operating at 2.45 GHz have been presented in this paper. Our design uses two apodized chirped transducers, which are nonequidistantly sampled. Improvements in the manufacturing processes make the production of these devices possible. New techniques in optical lithography, like OAI , phase-shifting mask technology, or optical proximity correction and advanced resist processing will lead to the successful and cost-effective production of SAW devices below the quarter-micrometer range. As we have demonstrated, it is feasible to construct SAW devices that exhibit a flat passband response over up to 800 MHz and excellent group-delay characteristic. Experimental and theoretical results are in good agreement. Based on these 2.45-GHz delay lines, we developed a radar system with adaptive phase-error compensation. This new system approach overcame typical performance limitations caused by VCO phase noise and achieved a high dynamic range for long-distance measurements.

ACKNOWLEDGMENT

The authors wish to thank W.-E. Bulst, Corporate Technology, Siemens AG, Munich, Germany, and V. Mágori, for their continual encouragement. Experimental devices were fabricated by B. Bienert, EPCOS AG, Munich, Germany, and H. Zottl, EPCOS AG, Munich, Germany. Many thanks to K. Wager, EPCOS AG, Munich, Germany, for help in the design of the SAW devices, M. Nalezinski, Corporate Technology, Siemens AG, Munich, Germany, and O. Sczesny, Corporate Technology, Siemens AG, Munich, Germany, for designing the IF circuits of the radar system, and J. M. Reindl, for the proofreading of this paper's manuscript.

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