Design, Fabrication, and Application of GHz SAW Devices

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Abstract - **To meet the increasing demand of high performance filters in GHz radio communication systems, we have improved design techniques and fabrication processes. Different types of filters in the range of 1 to 3 GHz, a 2.45 GHz resonator with 18 dB insertion attenuation and a quality factor of 1500, wideband delay lines at 2.45 GHz with 400 MHz and 600 MHz bandwidth, identification tags at 2.45 GHz, and ladder type bandpass filters for PCS and WLAN applications at 1.9 GHz and 2.45 GHz, were developed and manufactured. It will be shown, that these devices with submicron linewidth transducers down to 0.3 µm can be manufactured with tight process tolerances.**

I. Introduction

The rapidly accelerating growth of new radio services like cordless and cellular telephones, wireless LANs, remote tagging, satellite communication (e.g. GPS) and diverse ISM-applications rapidly have filled the frequency bands in the range up to 1 GHz. Growing numbers of subscribers and the need of faster data transmission require expanded bandwidths. Hence frequencies for mobile services go up well above 1 GHz, e.g., the ISM band at 2.45 GHz. Consequently components must operate at these higher frequencies still offering the well-known excellent performance. At the same time costs have to be extremely low as these devices are used mainly in products for the consumer market.

SAW technology offers a high potential to meet the very tight performance requirements. The demand for cost efficient fabrication for frequencies up to the lower GHz range can be met. Single crystal substrates provide an excellent quality factor that permits to achieve low loss devices with steep transition to the stopband. Furthermore, advanced lithographic fabrication processes, used worldwide in semiconductor industries, help to achieve high volume manufacturing.

To fulfill the system requirements, severe design and fabrication challenges have to be overcome. E.g., for RF filters resonant techniques are employed to reduce the insertion attenuation and to reduce the size of the devices at the same time. As the center frequency of SAW devices is directly related to the linewidth of electrodes in the SAW transducers and to the propagation velocity of the SAW on the substrate, linewidths of less than 0.5 µm are necessary. High reproducibility of the metal electrodes of 0.5 µm or less is crucial to the applicability of SAW devices. These electrodes have to be of some 0.1 µm thickness with less than 1% variation and must be stable at high current density and high acoustic strain.

Four examples will demonstrate the state of the art: resonators for ISM applications, RF filters for mobile communication, an IF delay line for radar systems, and ID-tags for train identification. It will become evident that design abilities as well as the fabrication processes have reached a high level already with still a fair number of possible improvements in the future.

II. Fabrication of the Devices

SAW devices operating up to 2.45 GHz in the fundamental harmonic require a submicron patterning process [3]. Optical projection printing in conjugation with a liftoff-process using a single resist layer technique is used with regard to high-volume, low-cost, and high-yield production.

Most important for the successful fabrication of the GHz devices was the appropriate configuration of the exposure tool, a i-line waferstepper (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 some off-axis-illumination (OAI) techniques. Adequate quadrupole illumination of the reticle, optimized by aerial image simulation [4] for the given linewidth of 0.3 µm have improved the DOF significantly.

To create liftoff patterns a high resolution positive tones resist, e.g., THMR-iP3250 was exposed by this waferstepper and developed with TMAH developer solution. In an geometrical optimized, quartz balance controlled electron beam evaporation system aluminum layers from 25 nm up to 0.8 µm were deposited with an accuracy of about 1 % over the wafer. Liftoff was carried out by dissolving the remaining resist in N-methyl-pyrrolidone.

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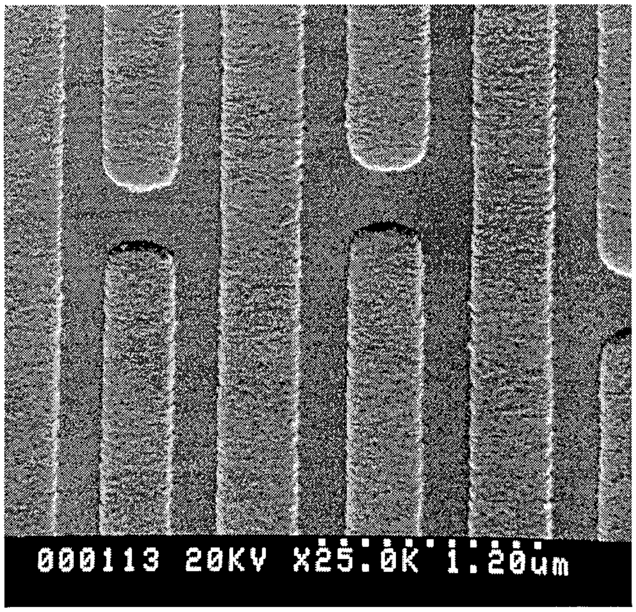

Fig. 1: SEM photograph of part of the IDT (0.6 μm periodicity and 0.4 μm linewidth).

For measurement of the devices the wafers had to be diced and the single chips were assembled in TO-39 and small SMD-packages.

Fig. 1 shows a SEM photograph of a part of the 0.3 μm IDT pattern made with the described fabrication process. It demonstrates high resolution and good edge quality of the liftoff process.

III. EXAMPLES

A. RESONATOR FOR THE ISM BAND AT 2.45 GHZ

SAW resonators are chosen as frequency stabilizing components in VHF and UHF oscillators because of their superior performance relative to LC resonators and low cost compared to bulk-wave crystal resonators. In the feedback loop of an amplifier, 2-port resonators determine the oscillator frequency and guarantee an excellent signal-to-noise ratio. When used as 1-port devices, they serve as narrowband frequency-variable resistors and are generally connected between the base of a transistor and the ground to stabilize the current consumption of the transistor.

SAW resonators operate in the fundamental mode in a frequency range from 200 MHz up to 2.5 GHz. Typical insertion attenuations for 2-port devices are about 7 dB at 200 MHz and 18 dB at 2.5 GHz. The loaded quality factor at 50 Ω decreases from 11000 at 200 MHz to 1500 at 2.5 GHz.

Fig. 2 shows the frequency response of a 2-port device at 2.45 GHz with an insertion attenuation of 18.0 dB and

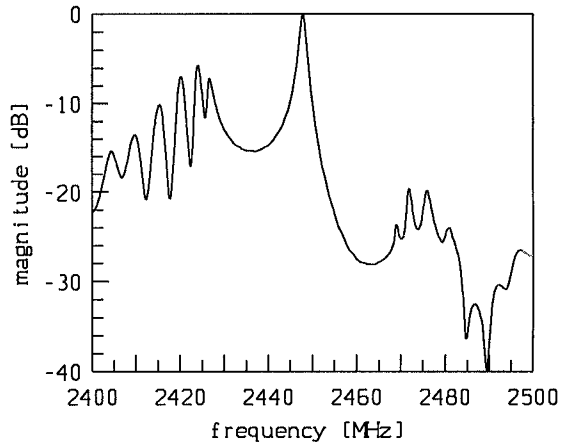

Fig. 2: SAW resonator at 2.45 GHz.

quality factor of approximately 1500. As is typical for all resonant structures, the SAW resonator is extremely sensitive to crystal quality and fabrication tolerances. Nevertheless, frequency tolerances as small as ±175 ppm are achievable with high yield. Owing to these extremely small tolerances, SAW resonators are widely used in highly stable microwave systems. Especially considering the trend towards higher frequencies, they have become very attractive for high-volume, low-cost remote control applications such as keyless entry systems, home and car security systems and medical alert devices.

B. DELAY LINES FOR A RADAR SYSTEM

The delay lines operating at the third harmonic were designed on the rotated cut of $LiNbO_3$. Two different bandwidths of 400 MHz, and 600 MHz were completed. The devices with a bandwidth of 400 MHz and 600 MHz have been fabricated and measured (Fig. 3). These 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 fabrication processes. Therefore we decided to use normal finger, which resulted in linewidths close to 0.3 μm. Using the YZ-cut of $LiNbO_3$ and an appropriate metallization height [2] reflection free IDTs were designed. As can be seen in Fig. 4 reflections over the passband are low. Further effort has to be spent on the investigation of the effects 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 in future designs. Nevertheless, the group delay linearity of this filter is excellent.

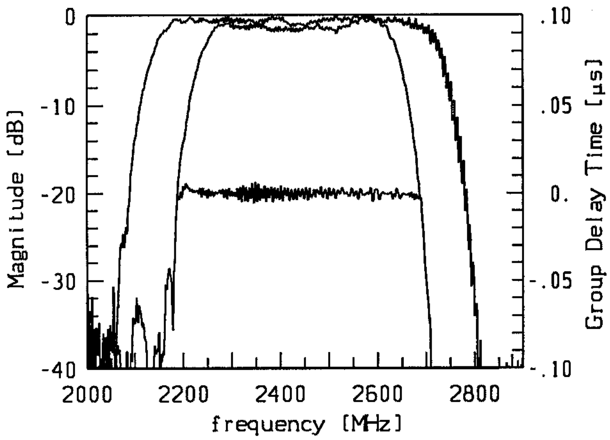

Fig. 3: Measured frequency responses of two delay lines at 2.45 GHz with bandwidths of approximately 400 MHz and 600 MHz, respectively.

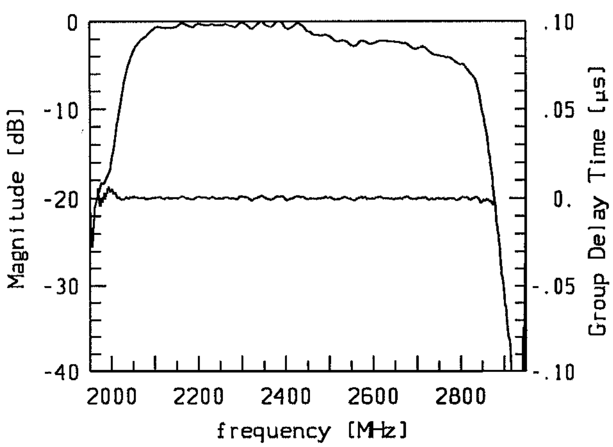

Fig. 4: Measured frequency response of the delay line operating at the fundamental harmonic.

C. ID-Tags for Train Identification

SAW devices allow the design of robust and passive identification marks. A high frequency electro-magnetic wave (RF interrogation signal) emitted from the interrogation unit is received by the antenna of the SAW transponder. The interdigital transducer (IDT) which is connected to the antenna transforms the received signal into a SAW. The SAW propagates on the crystal and towards the reflectors. The reflectors are placed in a specific pattern (like a barcode) which reflect parts of the incoming wave. What returns to the IDT is a high frequency series of echoes, which are transduced back into an electro-magnetic signal. This is the response signal which is sent through the antenna and back to the interrogation unit. The RF response carries the information about the places and numbers of reflections.

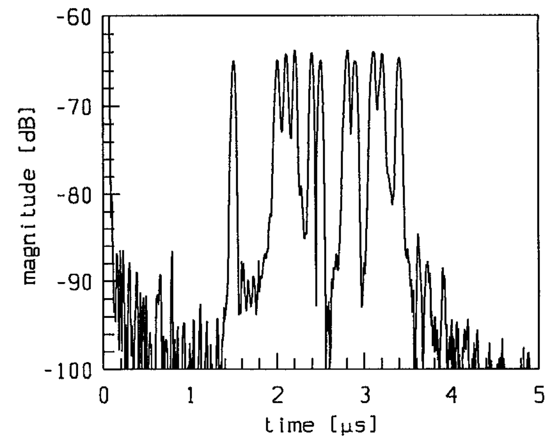

Fig. 5: SAW ID tags at 2.45 GHz.

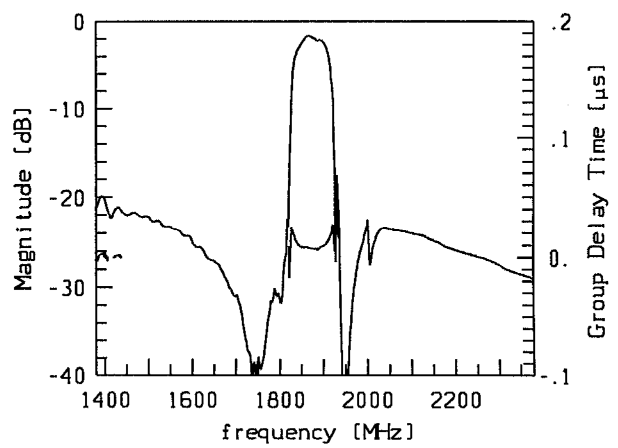

Fig. 6: Measured frequency response of a PCS Tx filter.

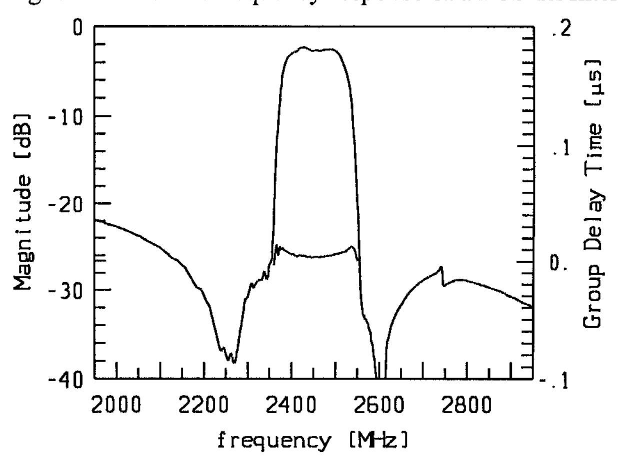

Fig. 7: Measured frequency response of an experimental ladder-type SAW devices.

The interrogation unit evaluates the amplitude, frequency, and time of the signal and determines the identification number. Fig. 5 shows a typical response signal of a SAW ID-tag together with the interrogation impulse at 0 μs and the bits from 1.5 μs to 3.5 μs.

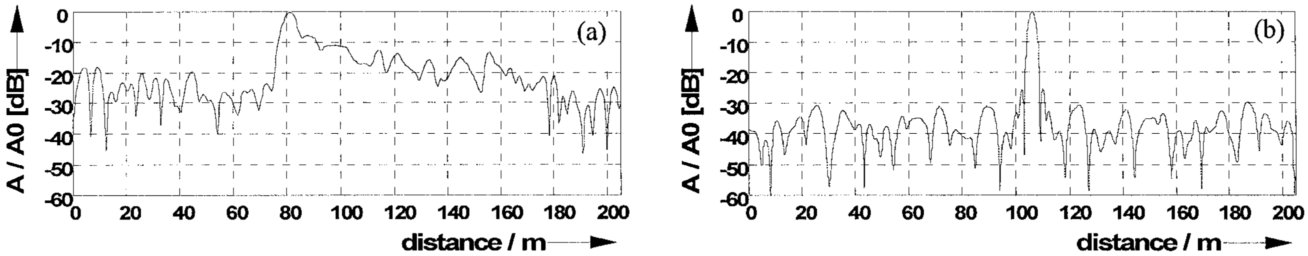

Fig. 8: Measured target echo (left). Same target echo after phase error compensation (right).

D. RF-Filter for PCS and WLANs

As an RF filter for the ISM band, e.g., WLANs, at 2.45 GHz a ladder type SAW filter may be used [1]. In a ladder type filter the SAW is used to generate impedances which change rather fast over the frequency band. This technique allows the design of low-loss filters at RF frequencies. The bandwidth is limited by the electro-acoustic coupling factor. In Fig. 6 the frequency response of a ladder type filter for PCS in the Tx path, and in Fig. 7 the measured frequency response of an experimental filter at 2.45 GHz are depicted. The usable bandwidth is more than 100 MHz and the insertion attenuation is close to 2 dB.

IV. Applications

For commercial microwave applications, inexpensive sensor designs are required. FMCW sensors operating with linear frequency modulated continuous wave offer a cost-effective measurement of distance and speed. However, the performance of conventional FMCW sensors is limited by the frequency linearity and the phase noise of the VCO [5].

Taking advantage of the reported 2.45 GHz delay lines, we built a novel type of FMCW radar 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. 8 illustrates the effect of phase errors on the FFT echo spectrum of a target at a distance of about 100 meters. Due to these phase errors, the raw target echo (a) is spread over a wide bandwidth. After phase error compensation, the same echo is compressed to a narrow peak (b). In experiments, performed with noisy 77 GHz MMIC VCOs [8], the proposed linearization technique proved to significantly enhance the dynamic range of conventional FMCW sensors, particularly for far away targets.

V. Conclusions

SAW devices offer at frequencies up to 3 GHz superior performance. We have presented resonators at 2.45 GHz with a Q factor of 1500, precise delay lines with bandwidths up to 600 MHz, ID tags for train identification, and bandpass filters for PCS and WLAN applications.

Improvements of the fabrication process made the production of the GHz devices possible. New techniques in optical lithography, like off-axis illumination, phase shifting mask technology or optical proximity correction and advanced resist processing will lead SAW device fabrication to and below the quartermicron range.

VI. References

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