Hyperbolically frequency modulated transducer in SAW sensors and tags

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A linear frequency modulated transducer was earlier proposed for use in surface acoustic wave (SAW) tags and sensors. This reported work demonstrates that the hyperbolically frequency modulated (HFM) transducer has significant advantages for such devices often operating in a wide range of temperatures. The HFM transducer is practically insensitive to wide temperature variations, which expand or compress signals in time. Owing to the exponential change of the varying period with the electrode number, the expansion of the length of all the periods is equivalent to just a shift in time and the compressed signal remains practically unchanged in shape, just slightly shifted. Such a shift has no importance for SAW sensors/tags, which usually operate on the difference of delays of the compressed peaks.

Introduction: The idea to use chirp interdigital transducers (IDTs) and corresponding linear frequency modulated (LFM) signals in surface acoustic wave (SAW) tags and sensors was proposed some years ago [1]. It is especially attractive for ultra-wide-band devices [2, 3] (Fig. 1) since significant processing gain $B \times T$ can be obtained compared to environmental parasitic reflections and thermal noise, (B being the used frequency band of the chirp signal and T its duration).

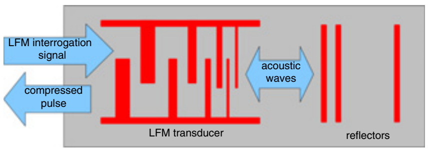

Fig. 1 *SAW reflective delay line sensor with chirp transducer*

The lithium niobate ($LiNbO_3$) substrates often used for such devices have a large temperature coefficient of delay and the increase of the delay with temperature is accompanied with a decrease of frequency, generating a change in the MHz/µs slope of dispersion of the LFM transducer. This, finally, results in additional losses, the broadening of compressed signals and/or complicated reader algorithms, especially because the sensor temperature is usually unknown in advance. The use of hyperbolically frequency modulated (HFM) signals was proposed many years ago [4] for time-invariant signal compression in SAW compression and expansion filters. However, [4] describes only the signal properties, while the design of such devices has not been disclosed. In addition, for applications in radars, instead of reflective array compressors (RACs) such devices might have a visible drawback – the compressed pulse would shift with temperature. In this Letter, we demonstrate that the HFM transducer is ideal for SAW sensor and SAW tag applications. In such a transducer, the local period of electrodes is linearly dependent on the coordinate of the electrode. It will be shown that it means exponential dependence of the period on the number of the electrode. The thermal variation changes all period proportionally, which for the exponential array means just a shift. Therefore such a transducer remains invariant to temperature.

Purely geometric problem: If the period of an array increases linearly with the coordinate, how can the coordinate, x_n of the nth element, of this array be calculated? One can write the following relation:

$$x_{n+1} - x_n = p_0 + \varepsilon\, x_n \tag{1}$$

wherein x_n is the coordinate of the centre of the nth electrode, p_0 the initial period, and ε is the linear grow or decay (if $\varepsilon < 0$) coefficient.

Suppose that the initial electrode ($n = 0$) is situated at the origin of coordinate $0X$, $x_0 = 0$, $x_1 = p_0$, formula (1) can be treated as an equation in integer numbers, which has the following unique solution:

$$x_n = \frac{(1+\varepsilon)^n - 1}{\varepsilon}\, p_0 \tag{2}$$

If we fix the first period p_0 and the last period $x_{N+1} - x_N = p_{\text{end}}$ and the total length of the structure L, the coordinate $x_n$can also be presented in the following form:

$$x_n = L\,\frac{p_0}{p_{\text{end}} - p_0}\left\{\left(\frac{p_{\text{end}}}{p_0}\right)^{n/N} - 1\right\} \tag{3}$$

For applications in SAW devices, such as RAC reflectors, with one reflecting element per wavelength, the periods of the structure are related to frequency as

$$p_n = \frac{V}{f_n}, \quad p_0 = \frac{V}{(F_0 - (B/2))}, \quad p_{\text{end}} = \frac{V}{(F_0 + (B/2))} \tag{4}$$

Here F_0 is the centre frequency, $|B|$ is the frequency band and V is the SAW velocity. If $B > 0$, the period decreases along the structure, and if $B < 0$, it is linearly increasing along the structure. The coordinate of the nth period x_n is given by

$$x_n = -L\,\frac{F_0 + B/2}{B}\left\{\left(1 - \frac{B\,V}{L\left(F_0^2 - (B/2)^2\right)}\right)^n - 1\right\} \tag{5}$$

Formula (5) can also be obtained considering the phase of the HFM signal [4]. The dependence on n is exponential in (3) and (5).

HFM SAW transducer: The above formula (5) is suitable, e.g. for devices having one reflector per wavelength. However, in a standard SAW transducer, we have a series of electrodes of alternating +/– polarity that is two electrodes per period. We can represent formula (5) in the following form for the coordinates of electrodes:

$$x_n = V\,T\,\frac{F_0 + B/2}{B}\left\{1 - e^{-\left(B/\left(2T\left(F_0^2 - B^2/4\right)\right)\right)n}\right\} \tag{6}$$

Numeric simulations: As an example, we have simulated numerically a HFM transducer using accurate FEM/BEM software. We use (Fig. 2) 128°-$LiNbO_3$ substrate 1 with the HFM chirp IDT 2 operating in the frequency range 200–400 MHz. The wide band transducer 3 is placed in the acoustic channel 4 of the HFM transducer allowing direct analysing of signals generated by the HFM transducer. The dispersive delay time T is equal to 0.5 µs, the $B \times T$ product thus being $B \times T = 100$. The period of the HFM transducer at the high-frequency end is 9.6 µm, linearly increasing with distance to a two times larger value at the low-frequency end of the chirp IDT. The transducer includes 279 fingers. The wide band standard IDT 3 including five electrodes with period $\lambda = 12.7$ µm is situated in 1000 µm from the HFM transducer on the high-frequency side of it. Both transducers have an aperture $W = 600$ µm.

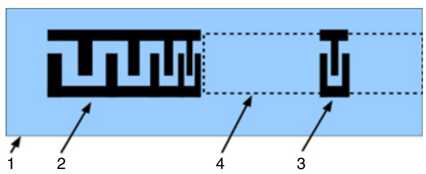

Fig. 2 *Geometry used in numeric simulation*

We have simulated the temperature effect on the delay line by increasing all dimensions in the propagation direction by 2% and decreasing the characteristic frequencies (F_0 and B) by 2% also. These changes roughly correspond to about a 250°C increase of the device temperature. Fig. 3 shows the impulse response of the devices. Expanded by 2%, the delay line has the longer response. However, the main part of this response is not only similar, but 'identical' to the initial response, when being shifted appropriately, as illustrated in Fig. 3. Namely, this feature of the HFM signal allows us to use the same 'matched-to-signal' filter [5] for all expanded copies of the initial signal. We have simulated the compression procedure numerically using only one, initial, signal for the creation of the 'matched-to-signal' filter.

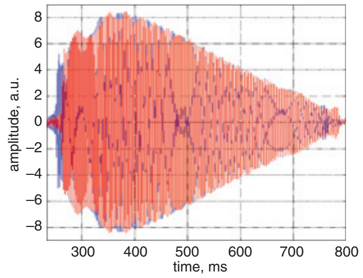

Fig. 3 *Simulated impulse responses*

The results are shown in Fig. 4. Both signals (initial, ideally matched to our filter, and extended by 2%) are compressed with the same amplitude and the width of both compressed peaks is identical (close to $1/B = 5$ ns at -3 dB). In practice, it means that the result is temperature-invariant; whatever is the temperature of the device, its response can be compressed by the same filter.

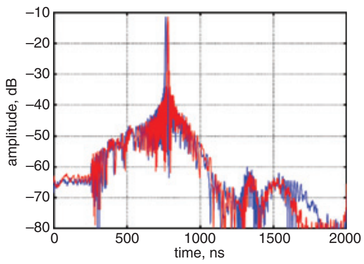

Fig. 4 *Compressed HFM pulses*

In SAW sensors (Fig. 1) or in SAW tags, the pulses reflected from a few reflectors are compared. Such a common for all reflectors shift of compressed reflected pulses is not so important, since the information is extracted from distance variation between the pulses.

We have repeated the same numeric experiment with a similar device, but with a LFM transducer. The amplitude of the compressed signal is in this case about 2.5 dB weaker and its width is about two times larger. For a larger $B \times T$ product, the degradation would be even more pronounced.

Conclusion: HFM signals and transducers (eventually reflectors) are ideally suitable for SAW sensors and SAW tags, since the compression of such signals, being temperature-invariant, can be always achieved with the same matched-to-signal filter, simplifying significantly the interrogation algorithm.

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One or more of the Figures in this Letter are available in colour online.

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