Evaluation of Digitally Coded Acoustic Surface-Wave Matched Filters

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Abstract—Acoustic surface-wave correlation filters for phase-shift-keyed (phase-coded) waveforms have been characterized. The filters were constructed using a surface-wave tapped-delay-line technique that resulted in highly compact devices. Both 7- and 13-bit Barker sequences have been fabricated on Y-cut LiNbO₃ for propagation in the Z direction. For purposes of evaluation, 20- and 30-MHz center frequencies were used with information bandwidths of 1.6 and 5.0 MHz, respectively. Measurements of the time and frequency domain responses, sidelobe levels, insertion loss, temperature sensitivity, and noise performance have been made. The results obtained closely follow theoretical predictions. Although some problems exist in the control of reflections and secondary generation of the signal, the feasibility of practical acoustic surface-wave digital filters has been demonstrated.

INTRODUCTION

A very desirable function to accomplish in signal processing for radar receivers and communications is the compression of the energy in a long pulse of RF into a shorter time. In radar systems, pulse-compression techniques are used to improve range resolution by permitting higher bandwidth signals to be used without requiring short-duration low-energy transmitted pulses (that is, without sacrificing detection range). In communications systems, pulse-compression techniques furnish a method for decoding digitally coded signals [1]. At present, the more commonly used pulse-compression filters have severe drawbacks; for example, dispersive acoustic delay lines [2] are generally expensive, bulky, and temperature sensitive, and have large insertion loss; while digital techniques are extremely expensive because they are complicated and they are limited in bandwidth because of the required switching times.

Considerable effort has been expended over the past few years on the application of generalized Rayleigh waves [3] for signal processing because of their potential advantages. A Rayleigh wave is an elastic surface wave that propagates along a stress-free plane surface of an isotropic elastic solid, having an essentially exponential decay in amplitude into the solid. Most of the particle displacement occurs within one wavelength of the surface; hence, the energy is concentrated there. For ease of coupling electrically to the surface waves, piezoelectric anisotropic substrates are generally used, since it can be shown [4], [5] that Rayleigh-type waves also propagate on these materials. For such piezoelectric substrates, coupling to the surface wave can be accomplished readily by means of deposited interdigital metal electrodes spaced one-half wavelength apart on the surface [6].

Many advantages can be gained by using acoustic surface-wave devices. The most significant of these are: 1) compactness, since the propagation velocity of the surface wave is 10⁵ times slower than the velocity of light; 2) simplicity of construction, giving promise of low cost; 3) high device uniformity, as the accuracy depends mainly on the photomask (for single crystal substrates); and 4) multifunction capability, as the wave is accessible for sampling along its entire path of propagation.

Successful synthesis of linear FM pulse compression filters using surface waves has already been reported [7]–[9]; however, less attention has been paid to discretely coded filters [10], [11]. Accordingly, in this paper we report the construction and evaluation of surface-wave matched filters for phase-coded Barker sequences at nominal frequencies of 20 and 30 MHz.

MATCHED FILTERS

The compression of an RF pulse is implemented through the use of a “matched filter,” in which the filter response is matched to the frequency, amplitude, and phase of the uncompressed waveforms [1], [2]. The uncompressed signal must be coded in one of several ways so that the output of the various sampling elements comprising the compression filter are only synchronously additive when the correct waveform is presented to the filter. Mathematically it can be shown that the impulse response of a matched filter is a time-reversed copy of the uncompressed waveforms, thus causing the filter to collapse the signal in time. It also can be shown theoretically that the ratio of peak signal power to mean-square noise power (white) at the output of a filter is maximized if it is a “matched” filter.

Several different types of coded waveforms have been investigated for use in pulse-compression systems. A commonly used waveform is the linear FM or “chirp” signal, in which the frequency of the uncompressed signal varies linearly from one end of the pulse to the other. Another important class of waveforms uses discrete coding in which a CW carrier is modulated in frequency, amplitude, or phase by a binary code sequence. This latter class of waveforms can be described by the following equation [2]:

\[ y(t) = \sum_{k=-\infty}^{\infty} a_k \sin(2\pi f_c t + \phi_k) \]

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where $P_n(t)$ represents unit pulses of fixed duration that are spaced sequentially in time, and $A_n$, $\omega_n$, and $\theta_n$ are the amplitude, angular frequency, and phase for the $n$th bit, respectively. A frequently used member of this class, which is the subject of this paper, is the phase-coded waveform in which the amplitude and frequency of each bit remains constant, while a $180^\circ$ phase shift is used to differentiate between ones and zeros in the binary code. Fig. 1 shows schematically the metallization pattern and corresponding waveform of such a surface-wave phase-coded filter. Electrodes requiring the same polarity are interconnected using the pads as shown; hence, the phase changes are implemented by having two adjacent electrodes from the same pad.

Realizable matched filters always have some output both ahead and behind the compressed pulse (the time sidelobes). Minimizing these sidelobes is a common design criterion in pulse-compression systems. One class of code sequences that has low-amplitude time sidelobes was described by Barker [12]. The sidelobes are lower in amplitude than the compressed pulse by a factor of $1/N$ where $N$ is the number of bits in the Barker code. They are therefore lower by $1/N^2$ in power. To illustrate this, a two-cycle-per-bit five-bit phase-coded Barker compression filter is shown in Fig. 2. As Barker codes are suitable for many applications, they have been well characterized [2]; consequently, they were selected for this study.

**Fabrication**

The matched filters were constructed using $Y$-cut platelets of lithium niobate for surface-wave propagation in the $Z$ direction. The platelets measured approximately $1 \times 5 \times 50$ mm. One major surface was polished optically flat to minimize any spurious reflections of the acoustic wave due to discontinuities such as scratches or pits in the surface. Although lithium niobate substrates are rather expensive at present, similar results can be obtained using inexpensive quartz substrates at the expense of increased insertion loss.

The matched filter and input transducer patterns, consisting of interdigital fingers, connecting lines and pads, were defined on the surface of the substrate using conventional photomasking techniques. The smallest dimension of the photomask was the interdigital finger width that was $28 \mu$m at $30$ MHz. Two different metal systems were used: i.e., aluminum approximately $1000 \ \AA$ thick, or a two-metal system consisting of a thin layer of a metal such as chromium or titanium for adhesion followed by a layer of gold approximately $3000 \ \AA$ thick for high electrical conductivity. The effects of the different metallization systems on device performance are discussed later in the text. Since only one metallization step is required for these devices, they are considerably easier to fabricate than multilayer semiconductor devices; also, extremely homogenous single crystal substrate materials can be obtained so that the repeatability of fabrication is mainly limited by the photomask alone.

Electrical contact to the interdigitated arrays was effected by using 1-mil [25-$\mu$m] bonding wires from the connecting pads to the coaxial launchers. A photograph of the overall device is shown in Fig. 3.

**Filter Evaluation**

**Impulse Response**

The simplest, most direct method for evaluating matched filters is to observe their impulse response, which is a time-reversed copy of the corresponding input signal. To simulate an impulse, a pulse narrower than one half cycle of the center frequency must be used. Accordingly, Fig. 4 shows the output of a 13-bit 30-MHz Barker filter when a 10-ns pulse was applied to the input. The output clearly shows the phase reversals of the time-reversed Barker coded sequence. The generated pulse is very sensitive to imperfections in the filter, and the distortion in the tenth bit is traceable to damaged fingers caused during handling the device. However, devices that are similar physically give very repeatable results.

A more detailed examination of these devices requires the use of the correct phase-coded Barker sequence as an input signal.

**Measurement System**

A block diagram of the phase-coded waveform generator is shown in Fig. 5. A variable-frequency phase-coded waveform generator is necessary because both the time response and frequency characteristics of the filters are to be investigated. The circuit is based on a double-balanced mixer that has the function of both an RF switch and a $180^\circ$ phase shifter. The divide-by-$N$ counter generates a pulse train at the desired digital bit rate that is synchronous with the CW input signal. Any
value of \( N \) between 1 and 32 could be selected. The 50-bit code generator is a shift register containing the desired digital code that controls the phase of the RF output signal. The divide-by-50 counter and the triggered pulse generator produce a synchronous gating pulse that turns the RF output on and off at the beginning and end of the desired phase-coded waveform.

**Time-Domain Response**

Figs. 6 and 7 show the phase-coded input signal (generated as described above) and the corresponding output signal for both a 13-bit and a 7-bit Barker filter. The theoretical output is shown below each photograph. Two of the more important parameters that can be obtained from these results are the pulse compression ratio and the maximum sidelobe level. As predicted theoretically, the pulse compression ratios are found to be 13 and 7 for the two filters, respectively. The maximum sidelobe level for the 13-bit filter is 21 dB below the correlation peak compared to a theoretical 22.3 dB; while for the 7-bit filter the maximum sidelobe level is 14 dB down compared to a theoretical 16.9 dB. These two photographs are typical of surface-wave filter responses in that the leading sidelobes and the compressed pulse closely follow the theoretically predicted values, while the trailing sidelobes are somewhat distorted.

Part of this distortion is caused by secondary acoustic generation, that is, the regeneration of unwanted surface waves by the electrical output signal across the interdigital filter pattern. This effect is most noticeable in the trailing sidelobes because the regeneration is strongest during the central correlation peak when the electrical signal is largest. Regeneration can be reduced by using a substrate material with lower coupling coefficient such as quartz. However, the ensuing increase in input impedance would require more complex matching networks for these particular devices. Two other effects contribute to the distortion: first, attenuation of the signal as it propagates underneath the rather long matched filter; and, second, acoustic reflection due to
the mass loading of the surface by the metal electrodes. This latter effect is discussed in more detail below.

**Metallization Effects**

One important consideration in the evaluation of surface-wave devices is the effect of the metallization on their operating characteristics, since this metallization will cause a slight change in the velocity of propagation and some acoustic reflection.

Tiersten [13] has considered the problem of Rayleigh wave propagation in a system consisting of a continuous thin film on a substrate. The solution he obtained is dispersive, and the limiting velocities are controlled by the respective Rayleigh velocities of the two media. Experimental results on the velocity and attenuation of Rayleigh waves on Y-cut quartz using various metal films have been reported by Cambon and Quat [14]. Since aluminum has a velocity close to that of quartz, little change was observed as a function of the aluminum film thickness; however, the velocity for gold is considerably lower than that of quartz and a large change was observed.

Since the Rayleigh velocity of Y-cut lithium niobate is not too different from that of quartz (3.48 × 10^5 cm/s as compared with 3.1 × 10^5 cm/s), the two substrates are expected to give similar results. Thus, a comparison of filters fabricated using aluminum and gold metallization should show clearly the effect of different metallization on the operating characteristics.

The responses previously shown in Figs. 6 and 7 were for filters having an aluminum metallization approximately 1000 Å thick. Accordingly, filters were also fabricated using 3000-Å gold electrodes, and upon evaluation, two major differences were observed. First, the filters with gold electrodes operated at a slightly lower frequency than those with aluminum; i.e., the center frequency of the aluminum 13-bit filter was 29.34 MHz while that for the gold device was 28.99 MHz. The order of magnitude of this frequency change is consistent with the predicted velocity change for the interdigital structure in question.

The second effect was a slight increase in the level of certain sidelobes, which was attributed to increased acoustic reflections and scattering from the higher mass-density gold metallization. Since each bit must travel a different distance under the matched filter transducer before the main correlation peak occurs, the contribution of the various bits to the amplitude of the main peak will no longer be equal if the beam is attenuated for any reason, e.g., reflection loss, scattering loss, or energy coupled out into the electrical circuit. To investigate this phenomenon further, the phase of a single bit of the input coded waveform was reversed so that its contribution to the main peak was also reversed. By measuring the change in the peak after such a reversal, the contribution of that bit can be measured. The results obtained are shown in Fig. 8, which is a plot of the change in the correlation peak for both the 7-bit gold and the 7-bit aluminum filters when each of the 7 bits is phase-reversed. For an ideal 7-bit filter, this change in correlation peak should be constant at 3 dB. Although some variation from 3 dB is observed in the case of aluminum, the change is clearly much greater with gold. This shows that the effect of the mass loading of the surface is not insignificant, but is minimized by using low mass metals, as expected.

**Variation of Compressed Pulse With Frequency**

As the frequency of the input coded waveform is varied, the filter will no longer be matched to it, causing the shape of the compressed pulse to change. The amplitude of the filter output signal can therefore be plotted both in time, as in Fig. 6, and in frequency. The variation of amplitude as a function of these two variables is called the response function or radar uncertainty function of the filter.

To determine the form of this response function, the frequency of the coded input signal waveform was varied around the center frequency, and the amplitudes of both the compressed pulse and the maximum sidelobe level were recorded. Seven- and 13-bit phase-coded filters were measured and the results obtained from the 13-bit pattern are shown in Fig. 9. It can be seen that the peak of the compressed pulse decreases with increasing frequency deviation and the sidelobe level increases. It was found that the variation of the compressed pulse with frequency closely follows that expected for a long linear filter having 78 (6 × 13) pairs, i.e., the first minima occurs at frequencies given by f_n ± f_0/78. This is to be expected. The sidelobe level is seen to rise to within 5 dB of the correlation maximum. Similar results were obtained for the 7-bit filter.

To show more clearly the experimental response function obtained, a composite photograph has been constructed that is shown in Fig. 10. Here the photographs of the time domain response, taken at various frequencies around the center frequency, are arranged to give a three-dimensional effect in amplitude, time, and frequency. This result compares favorably with the theoretical response for a 13-bit Barker pattern as shown, for example, in [2].
JONES et al.: DIGITALLY CODED ACOUSTIC SURFACE-WAVE MATCHED FILTERS

Effect of Ambient Temperature Variation

The change in response function with ambient temperature is an important characteristic in the evaluation of a matched filter. Quantitative evaluation of a 13-bit Barker filter was made by placing the device in an oven, varying the temperature between $-25$ and $+75\,^\circ C$, and recording the frequency of maximum correlation. The results obtained are shown in Fig. 11. The effect of this shift in correlation frequency on a constant-frequency coded signal input would be to decrease the correlation peak and increase the sidelobe level in a way predicted by Fig. 9, using the deviation frequency of Fig. 11.

Since the frequency of maximum correlation of the filter is determined by the interdigital periodicity and the velocity of propagation, any change in either quantity will result in a shift in frequency. Any change in the interdigital spacing is determined by the thermal expansion coefficient and would lead to a temperature sensitivity of approximately $2 \, \text{ppm/}^\circ C$ along the Z axis of lithium niobate. The observed shift is about $90 \, \text{ppm/}^\circ C$ and is, therefore, largely due to a change in velocity. This result is in good agreement with previously published thermal sensitivity data for this material [15].

The observed frequency deviation is seen to be rather high, and in most applications ambient temperature control will be necessary. However, certain specific cuts of various substrates could be used to minimize this temperature sensitivity, probably at the expense of insertion loss. For example, two zero-temperature-coefficient cuts for surface-wave propagation are known to exist for quartz (a weak coupling material relative to lithium niobate).

Insertion Loss

The insertion loss of surface-wave matched filters is made up of several contributions, i.e., 1) loss at the input transducer, 2) loss at the coded filter transducer, 3) surface-wave propagation loss, and 4) loss due to beam spreading. The first two were most significant for our devices while the last two were relatively small. The latter is confirmed by previously reported results [16] which show that the propagation loss and beam spreading loss are small for devices having dimensions and operating frequencies similar to ours.

The loss at either transducer is due to two different effects; first, the acoustic bidirectional nature, that accounts for $3 \, \text{dB}$ of loss; and second, electrical mismatch, that accounts for the remainder. The first of these is very difficult to circumvent in wide-bandwidth systems, but the second can be overcome, at least partially, by using standard electrical matching techniques. A complete discussion of matching to the input transducer while maintaining the required bandwidth is outside the scope of this paper, but has been discussed by others [6]. The major results of this analysis are the following: 1) for a small number of interdigital periods, the efficiency of an interdigital transducer is approximately
proportional to \( N \), where \( N \) is the number of interdigital periods; 2) the bandwidth is inversely proportional to \( N \). Hence, for a given substrate material, the efficiency–bandwidth product is a constant, and the bandwidth requirements for a particular information rate limit the efficiency of the transducer.

It can be shown that the transfer function of a matched filter (Fourier transform of the impulse response) is the complex conjugate of the spectrum of the signal to which it is matched [1]. That is, the frequency response (amplitude versus frequency) of the matched filter is identical to the spectrum of the input signal. Thus, we determined experimentally the required input transducer bandwidth by measuring the frequency response of the matched filter using a single-pair input transducer and a sweep generator. Since the single-pair transducer has a bandwidth approaching 100 percent, it should not affect the measurement significantly. The results for the 13-bit 30-MHz pattern are shown in Fig. 12. The vertical scale is logarithmic with sensitivity of 10 dB/div and the horizontal scale is 3 MHz/div centered at the midpoint of the filter. The first two nulls in the response occur at 5 MHz either side of the center frequency, a result that corresponds to the 5-MHz bit rate for this filter.

Based on previous work on phase-coded signal processing [17], a sufficient bandwidth to accommodate the information contained in the Barker pattern is equal to twice the digital bit rate, i.e., 10 MHz, for the 13-bit filter shown above. Thirteen-bit filters were built with both single-pair and three-pair transducers, since a three-pair transducer at 30 MHz has a 10-MHz bandwidth. The only distortion observed with the three-pair input was a slight rounding of edges of the compressed pulse and the sidelobes, confirming that the bandwidth restriction using a three-pair transducer was very small.

The impedance of transducers having less than 10 fingers at 30 MHz was rather high, resulting in a significant mismatch loss to a 50-ohm system. For example, the insertion loss to the correlation maximum for the 13-bit 30-MHz device using a one-pair input transducer was 37 dB, and for a three-pair transducer, 26 dB. Similarly, for the 7-bit 20-MHz device, using a one-pair input transducer, the insertion loss was 34 dB.

The use of a broad-band matching network will reduce this loss significantly. We have obtained some results using a simple pi matching network that reduced the loss to the correlation peak for the case of the 13-bit 30-MHz filter having a three-pair input transducer from 26 to 5 dB. (Note that this is not a true measure of the CW insertion loss due to the 11-dB compression gain.) The bandwidth of the matching network caused only a small amount of distortion of the compressed pulse; however, similar matching to higher-impedance single-pair transducer resulted in considerable distortion, as the matching network considerably reduced bandwidth.

Electrically tuning to the phase-coded transducer itself to reduce insertion loss is also possible, but the effect of this tuning on the filter characteristics is not known at present. The design of these filters assumes that the various fingers in the coded transducer act as taps in an ideal tapped delay line, which inherently assumes that each tap couples out a negligible amount of power. When this assumption is not satisfied, the wave is attenuated as it travels under the transducer; also, secondary acoustic generation occurs, as was discussed earlier. The filter characteristics will be distorted if either of these effects become appreciable.

This problem can be stated more precisely in terms of the Fourier transform of the filter response; i.e., it is necessary to determine the feasibility of uniformly increasing the Fourier amplitude while keeping the phase characteristic unchanged. To our knowledge, a satisfactory answer to this problem has not been found. In the work reported here, this effect was minimized by electrically terminating the filter transducer with a broadband 50-ohm system and accepting the increased insertion loss. Since these filters had performances close to that expected for idealized matched filters, and exhibited reasonable insertion loss, the use of this resistive termination proved to be successful.

Another characteristic of these devices that has to be considered along with the insertion loss is the direct electrical coupling from input to output. This was found to be better than -66 dB for the configuration shown in Fig. 3. This is expected to be more than adequate for most practical applications.

CONCLUSIONS

The main purpose of this study was to investigate the feasibility of using phase-coded surface-wave matched filters in a practical system. To this end, 7- and 13-bit Barker codes were used as vehicles for the investigation, and the results have shown that these matched filters closely follow the theoretical predictions. A pulse compression of 13 was obtained with a sidelobe level 21 dB below the correlation peak and an insertion loss to the correlation peak of 5 dB (discounting the compression gain, this corresponds to an insertion loss of 16 dB).

The advantages to be gained by using these devices are numerous. Probably the most significant advantage is their compactness, since the overall dimensions of each of the devices described was only 1 × 2 × 3 cm, including the connectors, although no special effort had been made to minimize the size. The electrode pattern itself
was typically $5 \times 10$ mm. Another advantage is the simplicity of fabrication that should result in high-yield low-cost devices. Other advantages include the flexibility of realizing many different functions and moderate insertion losses.

There are also some disadvantages associated with these devices; for example, their temperature sensitivity has been measured and is rather high. The problems of internal reflections and secondary generation have also been noted, and further work is presently being carried out to find ways to minimize these.

There are also some parameter limitations, such as the restriction in substrate size usable at present. For lithium niobate, this is considered to be approximately $10 \times 2 \times 0.2$ cm; however, as this corresponds to a limitation of 600 bits of 5 cycles per bit at 100 MHz, it is not excessively restrictive. Fabrication problems limit the maximum center frequency to approximately 1 GHz at present ($\sim 1$-µm-wide lines), which in turn limits the available bandwidth, implying a limitation of $600 \text{ bits} \times 5 \text{ cycles/bit} \times 100 \text{ MHz} \approx 0.1 \text{ GHz}$. Hence, the minimum compressed pulsewidth (since the compressed pulsewidth + $\Delta f$) is

The feasibility of using surface waves for realizing phase-coded matched filters has been demonstrated and the results indicate that the performance is theoretically predictable. Due to the inherent flexibility of surface-wave devices, many other filter impulse responses can be realized. The successful results given here imply that similar success may be expected for other filter applications.

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**References**