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# Bandpass Filters Using Nonlinear FM Surface-Wave Transducers

J. C. WORLEY

***Abstract*—A generalized FM method of obtaining bandpass filters using surface-wave delay lines is discussed. Two identical FM transducers are used as input and output. The FM function of the transducers is determined by the required passband.**

It is well known that surface-wave delay lines (SWDL) can be used in a wide variety of filter types [1]. One of the most promising areas of application is bandpass filters [2]. Through a relatively simple technology, it is possible to synthesize quite complicated and exact bandpass functions. This short paper discusses one of several possible methods of obtaining this type of filter with a SWDL, a so-called nonlinear FM technique.

The most common and straightforward method of obtaining bandpass filters from a SWDL is a time domain replica approach. In this method one of the transducers is designed so that it has an apodization similar to the Fourier transform of the desired frequency response and all fingers resonant at the center of the band. The second transducer is a standard interdigital transducer with a bandwidth large enough so that it does not affect the overall response of the delay line. For example, if one desired a rectangular passband, the replica transducer would have a sin $x/x$ apodization.

This approach has the distinct disadvantage that there are fingers in the transducer which have small overlap, some approaching zero, which in turn leads to large diffraction losses. This can possibly be neglected if one uses a focusing material such as $LiNbO_3$. However, this restricts the type of material which can be used, eliminating *ST* quartz, $Bi_{12}GeO_{20}$, and ceramics.

A solution to this difficulty can be found in signal processing theory. It is possible to code the two transducers with an FM signal and then by arranging them as time translates of each other, i.e., so they will autocorrelate. A frequency response results which is not an FM but just the spectrum amplitude of the FM with a linear phase. In other words, with this method the bandpass response of the delay line can be determined by the manner in which the center-to-center spacings of the fingers are graded, independent of the overlap of the fingers. A delay line of this type is shown in Fig. 1. The design shown in Fig. 1 does use a small amount of finger apodization near the transducer ends. However, this apodization is used only to smooth out the effects of passband ripple.

To obtain the desired frequency response, one must specify the corresponding FM function. This requires the Fourier transformation of a frequency domain envelope function into a time domain FM function with an arbitrary envelope. This can be done through the use of stationary phase [3]. A detailed theoretical derivation of this principle is given in [2], and only the pertinent equations will be shown here. The principle of stationary phase leads to the relation

$$\phi'(t) = 2\pi f(t) \tag{1}$$

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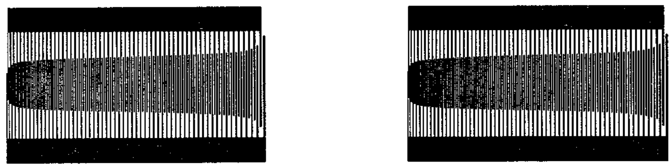

Fig. 1. Transducer pair for FM bandpass filter.

where $\phi(t)$ is the phase function describing the FM and $f(t)$ is a function derived as shown in the following paragraphs. A second equation, derived from Parseval's theorem

$$\int_{-\infty}^{f} |U(\xi)|^2 \, d\xi = \int_{-\infty}^{t} |u(\eta)|^2 \, d\eta \tag{2}$$

completes the equations necessary to find the desired phase function. Note that $U(\xi)$, which is the square root of the bandpass function, and $u(\eta)$, which is the square root of the time response of one transducer, are specified by the designer, and thus the time envelope of a single transducer is independent of the frequency response of the delay line. $\phi(t)$ is found by integrating (2) to give two new functions

$$P(f) = Q(t)$$

solving for $f$

$$f(t) = P^{-1}(Q(t))$$

substituting this into (1)

$$\phi'(t) = 2\pi P^{-1}(Q(t))$$

and integrating,

$$\phi(t) = 2\pi \int P^{-1}(Q(t)) \, dt + C.$$

As an example, consider the case of a rectangular passband and a constant time envelope:

$$|U(f)|^2 = 1, \qquad -\frac{\Delta f}{2} \le f \le \frac{\Delta f}{2}$$

$$|u(t)|^2 = \frac{\Delta f}{T}, \qquad -\frac{T}{2} \le t \le \frac{T}{2}.$$

Integrating (2) with these amplitude functions gives

$$\frac{\Delta f}{T} \int_{-T/2}^{t} d\eta = \int_{-\Delta f/2}^{f} d\xi$$

$$\frac{\Delta f}{T}\left(t + \frac{T}{2}\right) = f + \frac{\Delta f}{2}.$$

Inverting the preceding equations and performing the integration indicated in (1) leads to

$$\phi(t) = \pi \frac{\Delta f}{T} t^2 + C$$

which is the phase function for a linear FM signal at baseband. This may be placed on a carrier by adding $\omega_0 t$ to the right side of the preceding equation.

An example of spectrum amplitude and time amplitude functions which lead to a nonlinear FM function is

$$|U(f)|^2 = (1/\pi W)/\sqrt{1 + (f/W)^2}$$

$$|u(t)|^2 = 1/\sqrt{T}, \qquad 0 < t < T$$

where $W$ is the 3-dB bandwidth [2]. The corresponding phase function is

$$\phi(t) = 2\pi W \int \tan\left[\frac{\pi}{2}\left(1 - \frac{t}{T/2}\right)\right] dt + C.$$

Fig. 2 shows the theoretical and experimental response of a delay line with a pair of transducers defined by the preceding phase function. The dashed curve is the desired response, and the solid curve is the theoretical response of the delay line as predicted by an equivalent circuit model. The circles are experimental points. Unfortunately, the leakage of the delay line was sufficiently high so

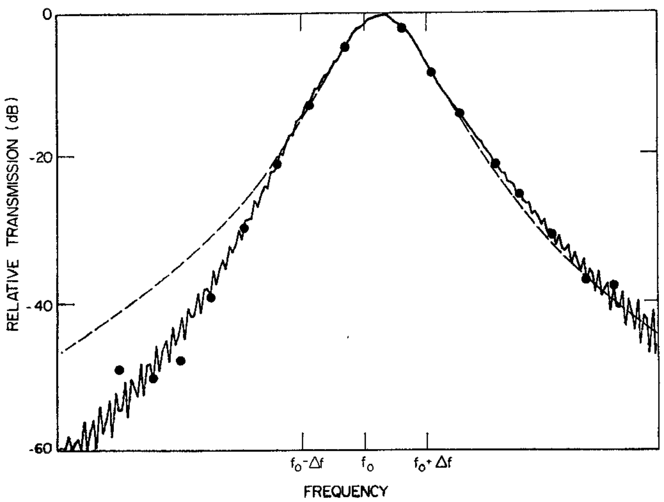


Fig. 2. Desired, theoretical, and experimental responses of bandpass filter.

that CW measurements were impractical, and long pulses at selected frequencies had to be used. The $LiNbO_3$ delay line had a center frequency of 30 MHz, a 3-dB bandwidth ($\Delta f$) of 5 MHz, and a finger grading which covers a frequency range of approximately 10–50 MHz. The unmatched insertion loss at the center frequency was 18 dB. The theoretical curve and the data show an asymmetry which is due to an improper compensation for the electrical mismatch of the graded finger spacing in the design (see [2]). This has been carried over to the theoretical curve to give an accurate comparison of theory with experiment.

This short paper has discussed a nonlinear FM technique for making SWDL bandpass filters. It has the advantage that very little or no apodization of the fingers is necessary, and thus diffraction losses of the delay line can be minimized. Further, it allows the designer the freedom to specify the time domain and frequency domain amplitude responses of a single transducer independent of one another. One disadvantage of these filters is that in practice their maximum center frequency is limited. This is because in an FM transducer the number of fingers required is determined by the center frequency and the time duration of the impulse response. Thus for applications with very high center frequencies, the number of fingers required may be more than can be practically fabricated. However, most applications occur in the range of 100 MHz or below where the number of fingers required is usually practical.

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# A Programmable Surface Acoustic Wave Matched Filter for Phase-Coded Spread Spectrum Waveforms

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***Abstract*—A programmable surface acoustic wave (SAW) matched filter for biphase-coded spread spectrum waveforms has been constructed using a temperature-stable *ST*-cut quartz tapped delay line (TDL) and silicon-on-sapphire integrated control circuits. Construction is hybrid with wire stitch bond interconnections between the acoustic and microelectronic portions of the device. The SAW TDL operates at 120-MHz center frequency with 100-ns spacing between adjacent taps for a 10-MHz chip rate. The output of each tap can be individually switched to a load with 0 or 180° phase shift by the silicon-on-sapphire integrated control circuits. The high-speed capability of silicon-on-sapphire integrated circuits allows programming (code changing) to be achieved with a serial data input at 10-MHz rates, while the low temperature coefficient of *ST*-cut quartz allows satisfactory operation over a wide temperature range (−25°C to +85°C).**

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## I. Introduction

Spread spectrum communication systems have been developed to provide efficient and reliable information transfer between source and receiver [1]. Waveform coding techniques are used to combat noise problems and to give security and multiple access capability [2]. Various waveform coding techniques are possible such as linear FM and phase-coded CW. Combinations of these waveforms in contiguous frequency channels and/or time-ordered sequences can be used. Whichever coding scheme is used, a necessary component in the receiver is the matched filter.

Surface acoustic wave (SAW) tapped delay line (TDL) matched filters for phase-coded waveforms have been developed with near-optimum performance and are now being incorporated in developmental spread spectrum communication systems. Current applications use fixed coded TDL's with center frequencies in the 30–200-MHz region with up to 511 taps for biphase-coded waveforms at 5–20-MHz chip rates. These basically passive devices have the advantages of low loss, small size, simplicity, and low cost when compared to previous TDL's utilizing bridged-T delay networks or electromagnetic cable delay lines. They are also significantly less complex than power-consuming digital processors which can perform similar functions.

To achieve the full potential of the TDL's and meet future system requirements, it will be necessary that individual taps of the TDL be programmable in order to process different codes [3]. It will also be highly desirable that the programming be accomplished in real time. That is, the TDL performing as a matched filter for an incoming phase-coded waveform must be switched rapidly enough to match another code without a time gap being required between the two received codes. This real-time programming capability will give security, immunity to multipath problems, and multiplexing capability. For many system applications additional requirements are low power drain and the ability to operate over a wide temperature range. For these reasons silicon-on-sapphire (SOS) technology has been used for the microelectronic control circuits and *ST*-cut quartz for the TDL.

SOS has a major advantage over other integrated circuit (IC) approaches in that parasitic capacitances are reduced to a minimum by virtue of the insulating sapphire substrate. High-speed IC's required for programmable tapped delay line (PTDL) applications can consequently be readily achieved. The piezoelectric acoustic medium (*ST*-cut quartz) was selected for its zero first-order temperature coefficient which allows device operation over the −25°C to +85°C temperature range with no significant variation in device performance.

The control microelectronics is described in Section II, and overall PTDL device performance is presented in Section III.

## II. SOS Integrated Control Circuits

A modular approach was used in the control circuit design to ensure reasonable IC yields and to achieve flexibility which would allow extension to larger numbers of taps. An IC die[1] design was selected which provides control for 16 taps of a TDL. The functional block diagram of this die is shown in Fig. 1 and its operation is as follows.

A data register accepts serial digital information representing the desired tap switch positions and holds this data indefinitely by activation of the HOLD command. Parallel shifting of the data into the storage register is then accomplished by application of a transfer signal $T$. The storage register controls the switch drivers which set the tap switches according to the input data. At the end of the hold

[1] The "die" terminology is used to avoid confusion between the normally used IC "chip" of the semiconductor industry and the waveform "chip" of communication systems.