PERIODIC FREQUENCY RESPONSE SAW FILTERS FOR A TREE APPROACH TO MANY-TONE FREQUENCY SYNTHESIS

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Abstract

A tree configuration using periodic-in-frequency SAW filters plus diode switches to achieve many-tone frequency synthesis is proposed. Design procedures are outlined for independent specification of center frequency and periodicity and limited-resonance periodic filters.

Introduction

Fast, compact frequency synthesizers are needed in a variety of electronics applications including communications, data link, and automatic test systems. Since SAW filters are particularly suited[1,2] to the implementation of these needs, we propose in the present paper a new frequency synthesizer concept using periodic, multi-resonances[3] SAW filters plus fast diode switches[4] in a tree configuration. In this way, a large number of output frequencies can be achieved with relatively few SAW devices.

In addition, design procedures for implementing the required filters will be discussed. Standard tapped or thinned filter theory and the experimental feasibility of periodic filter synthesis in the TACAN band will be reviewed. Theory for the independent specification of resonance center frequency and periodicity and for the achievement of a strictly limited number of periodic resonances[6] will be outlined.

Tree Configuration for Fast Frequency Synthesis

Recently it was shown that frequency synthesizers[1], comprised of SAW filterbanks[2] and SOS-PIN diode switch arrays[4], offer compact size, reliability and realization with mass producible components. However when the number of frequencies exceeds 100 a SAW filter and PIN-diode switch per frequency[1], is no longer practical. In this case our proposed tree approach having unique features over those previously discussed[3] becomes attractive. The basic configurations for single and multiple output operation are shown in Fig. 1. The basic attributes[1] of the SAW-SOS frequency synthesizer are retained and as shown in Fig's 1 and 2, only 48 SAW filters (4 filterbanks) and 48 PIN diode switches (4 arrays) are required to realize 256 possible frequencies.

The first level of SAW filters, denoted in Fig. 1 as filter banks A and B, are narrow band, periodic, multi-resonance filters. As shown in Fig. 2 each periodic filter picks out M (in the case shown M = 8) tones from the N available tones (N = 256). The rejection of the unwanted tones is achieved by properly aligning the filters' deep nulls with the undesired tones[1] or appropriately shaping[6] the filter. Since the narrow band filters are placed first in the chain all switching occurs after the narrow band filters and the switching speed is unaffected by the high-Q's of these filters.

The second level of SAW filters, denoted as filterbanks C and D are broad band filters with ideally rectangular shapes. In order to reduce spurious due to the overlapping of adjacent filter transition bands and to reduce the difficult shape factor requirement of such a filter, guard bands are introduced by portioning the overall band into alternating sub-bands as shown in Fig. 2. The white areas are the guard bands for those filters designed for operation in bands defined by the black areas and vice versa. In this way, rejection in excess of 50 dB can be achieved with filters designed for 2:1 shape factors at the expense of doubling the required number of filters and switches.

The operation of the tree frequency synthesizer is conceptually simple. Applying the appropriate logic words to couple filter A1 with filterbank C (Filter C1) results in an output of tone #1. Likewise tone #244 is obtained by coupling filter B16 with filterbank D (filter D2). This fundamental operation suggests a simple means for determining the frequencies (tones) passed by each filter and ultimately the bandwidths and center frequencies for each filter. The technique is to write sequentially the desired frequencies into two matrices; one for the white bands and another for the black bands.

$$\begin{array}{c} \\ A1 \\ A2 \\ \cdot \\ \cdot \\ Ak \end{array}\begin{array}{c} \begin{array}{ccc} C1 & C2 & CM \end{array} \\ \begin{bmatrix} f_1 & f_{k+\ell+1}\cdot\cdot f_{(m-1)k+\ell+1} \\ f_2 & f_{k+\ell+2} \quad\quad \cdot \\ \cdot & \cdot \quad\quad\quad \cdot \\ \cdot & \cdot \quad\quad\quad \cdot \\ f_k & f_{2k+\ell}\cdots\cdots f_{mk+\ell} \end{bmatrix} \end{array} \begin{array}{c} \\ B1 \\ B2 \\ \cdot \\ \cdot \\ B_\ell \end{array}\begin{array}{c} \begin{array}{ccc} D1 & D2 & D_p \end{array} \\ \begin{bmatrix} f_{k+1} & f_{2k+\ell+1}\cdot\cdot f_{mk+\ell+1} \\ f_{k+2} & f_{2k+\ell+2} \quad\quad \cdot \\ \cdot & \cdot \quad\quad\quad \cdot \\ \cdot & \cdot \quad\quad\quad \cdot \\ f_{k+\ell} & f_{2k+2\ell}\cdot\cdot f_{mk+\ell p} \end{bmatrix} \end{array}$$

where the total number of frequencies $N = mk+\ell p$

The columns define those frequencies which are to appear within the passbands of broadband filters $Ci(i = 1,m)$ and Dj $(j=1,p)$ while the rows define those frequencies which are to appear within the multiple pass bands of narrowband periodic filters Ai $(i=1,k)$ and $Bj(j=1,\ell)$. Using these matrices the 1 dB bandwidth of filter C2 is readily computed to be $f_{2k+\ell} - f_{k+\ell+1}$ and the multiple resonant frequencies (m in number) of filter A2 are f_2, $f_{k+\ell+2}$, ... , $f_{(m-1)k+\ell+2}$ with nulls spaced by $\pm\, q(f_2-f_1)$ off of resonance with q an integer.

Review of Tapped Filter Design

Realization of this frequency synthesis approach requires SAW filters having periodic frequency response curves. The straightforward technique for obtaining these is to use a tapped filter as illustrated in Fig 3a. The impulse response of this filter can be taken as an infinite sum of impulse responses of individual taps modulated by a finite duration time function e(t). That is

$$h_o(t) = \sum_k e\ (kt_o)\ \bar{h}\ (t + kt_o) \qquad (1)$$

where $t_o = 1/f_x$ is the tap period and, for the case illustrated,

$$e\ (kt_o) = \begin{cases} 1 & -\,Y \leq k \leq Y \quad (\text{and } Y = 4) \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$

The frequency response is obtained by Fourier transforming equation (1). Thus

$$H(f) = F\,\{h_o(t)\} = \bar{H}\ (f) \sum_{k=-Y}^{Y} e\ (kt_o)\ e^{j2\pi fkt_o} \quad (3)$$

where $\bar{H}(f)$ is the frequency response of a single tap.

Several important conclusions can be derived from equation (3). H(f) is the product of the wideband individual tap response $\bar{H}(f)$ and a periodic function $\Sigma\, e\ (kt_o)\ e^{j2\pi fkt_o}$. For the periodic train the bandpass characteristics of each response is determined by the envelope of the taps. This latter property comes by analogy with the well-known interdigital transducer finger overlap - frequency response relation[6]. For the case illustrated in Fig 3a the uniform taps imply a narrowband sin X/X response modulated by the wideband sin X/X tap response. This is theoretically illustrated in Fig 3b where the transducer of Fig 3a is taken as input and output. The inset to Fig 3b provides experimental confirmation using a filter fabricated[5] by direct projection (0.7μm lines) and again[2,5] demonstrates the feasibility of realizing periodic frequency response functions in the TACAN band.

For the present tree filter application, however, a difficulty is encountered with the simple periodic tap approach documented above. For real tap weights e (kt_o), that is unless phase shifters can be used on each tap[6], an individual narrowband response can be made to occur only at n/t_o or $(2n+1)/2t_o$. This follows from the requirement for a symmetric envelope function (to yield a linear phase frequency response) which in turn implies a symmetric frequency response about f = 0. However, the tree filter requires independent specification of frequency spacing (or period) and narrowband response center frequency. This independent specification is achieved using the following technique.

General Filter Design

Consider the modulated periodic time response of Fig 4a. The key is to avoid replacing each pulse with an individual tap and instead to sample[6] at times given by $t = N/2f_o$. This sets the center frequency at f_o. The sampled response can be written as

$$H_o\left[N\right] = \sum_{k=-Y}^{Y} e\left(\frac{k}{f_x}\right) \bar{h}\ (N/2f_o + k/f_x) \qquad (4)$$

where $H_o\left[N\right]$ represents the finger overlap function[6] at the Nth gap.

For example consider the waveform of Fig 4b. Since the exact shape of the modulating function H(f) is seldom critical, there is some freedom in the choice of $\bar{\tau}$. Here let $\bar{\tau} = 1/f_o$. $H_o\left[N\right]$ is then nonzero (and equal to unity) for

$$\left(\frac{2f_o k}{f_x} - 2\right) \leq N \leq \left(\frac{2f_o k}{f_x} + 2\right) \quad -Y \leq k \leq Y \qquad (5)$$

Taking f_o = 1086 MHz and f_x = 48 MHz for an f_o/f_x ratio of 22.625 along with Y = 8 results in the transducer shown in Fig 5a. Note the number of fingers in each "tap" varies as does the distance between "taps." The corresponding frequency response is shown in Fig 5b confirming the validity of the above analysis.

Limited Resonance Filter Design

For the approaches discussed to this point, the periodic filter resonances extend to infinity, although modulated by a wideband frequency response. If transducer apodization[6] is allowed, a finite number of resonances can be synthesized[6], for example just the five responses required for filter B1 of Fig 2. This can be shown as follows.

Using the Fourier series representation of a periodic time function $\hat{h}$ (t) yields

$$\hat{h}\ (t) = \sum_{k=-Y}^{Y} a_k\, e^{j2\pi ktf_x} \qquad (6)$$

where

$$a_k = f_x \int_0^{1/f_x} \hat{h}\ (t)\ e^{-j2\pi ktf_x}\, dt \qquad (7)$$

and $1/f_x$ is the period in the time domain.

To avoid an infinite transducer consider a modulated function

$$h_o(t) = e(t) \sum_{k=-Y}^{Y} a_k\, e^{j2\pi ktf_x} \qquad (8)$$

Using straightforward Fourier transform techniques[6]

$$H(f) = F\,\{h_o(t)\} = \sum_{k=-Y}^{Y} a_k\, E(f-kf_x) \qquad (9)$$

where $E(f) = F\,\{e(t)\}$.

For example consider the synthesis of the frequency spectrum of filter B1 shown in Fig 6a. With reference to equation (9) we see

$$E(f) = \frac{\sin 2\pi f}{2\pi f\tau} \qquad (10)$$

$$a_k = 1 \qquad -2 \leq k \leq 2 \qquad (11)$$

with $1/2\tau$ = 3MHz, $\tau = 0.166667 \times 10^{-6}$ sec, f_x = 48 MHz, and $1/f_x = 2.08333 \times 10^{-8}$ sec. Thus, by using equation (8)

$$h_o(t) = \left[1+2\cos 2\pi f_x t + 2\cos 4\pi f_x t\right]\left[U_{-1}(t+\tau) - U_{-1}(t-\tau)\right] . \qquad (12)$$

This function is plotted in Fig 6b. The corresponding sampled time function is

$$H_o\left[N\right] = \left[1+2\cos\frac{N\pi f_x}{f_o} + 2\cos\frac{2N\pi f_x}{f_o}\right] \quad -2f_o\,\tau \leq N \leq 2f_o\,\tau . \qquad (13)$$

The frequency response of a transducer using these $H_o\left[N\right]$ coefficients is shown in Fig 6c. Second order effects are neglected.

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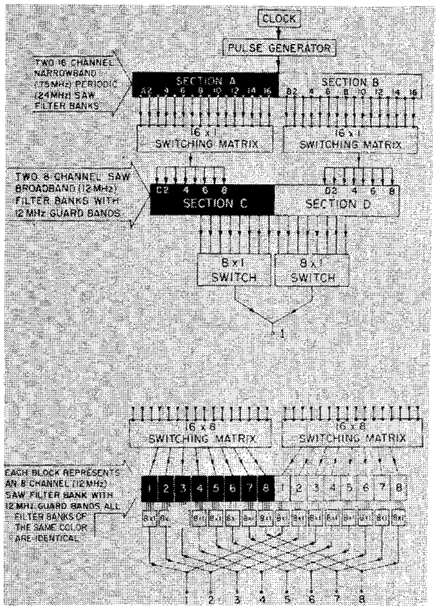


Figure 1a (top) Single output tree Configuration for Synthesizing 256 possible tones of which any one is available, upon appropriate instruction, at the output.
Figure 1b (bottom) Eight output tree configuration for synthesizing 256 possible tones of which any one is available, upon appropriate instruction, at each output. (Top section of 1a not repeated)

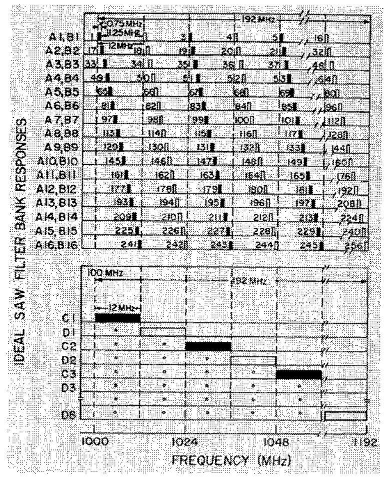


Figure 2. Ideal SAW filter responses for a TACAN 256-tone tree frequency synthesizer as per Fig. 1

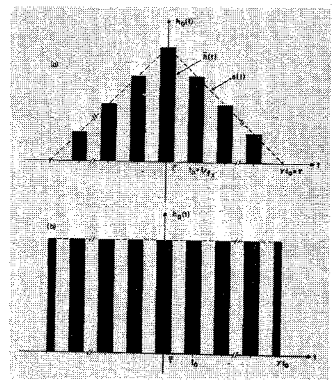
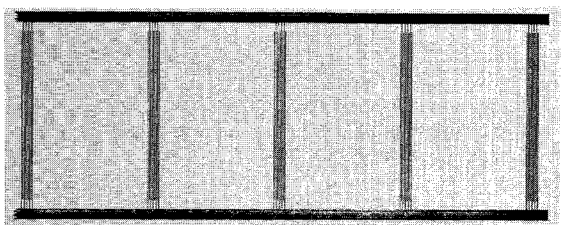


Figure 4a. (top) Example of a general truncated or modulated periodic time function.
Figure 4b. (bottom) Actual modulated periodic time function to be sampled in text.



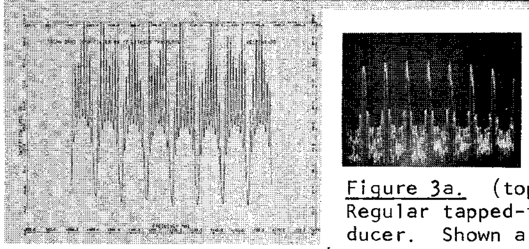
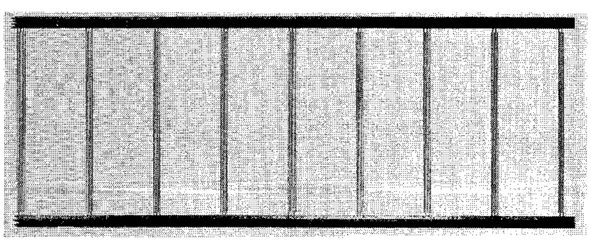


Figure 3a. (top) Regular tapped-filter transducer. Shown are center and right-half taps only ($0 \leq k \leq 4$). Figure 3b. (bottom) Filter frequency response with input and output transducers corresponding to above. Material: YZ $LiTaO_3$, Number of taps: 9, Tap spacing: 131.54μm, Linewidths: 0.71773μm. Experiment shown as inset.



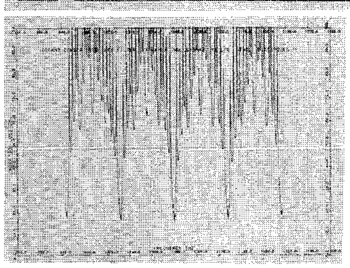
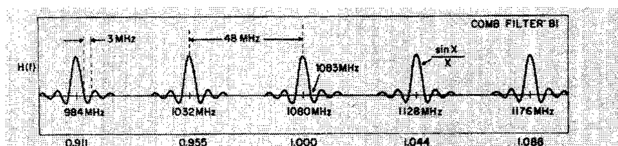
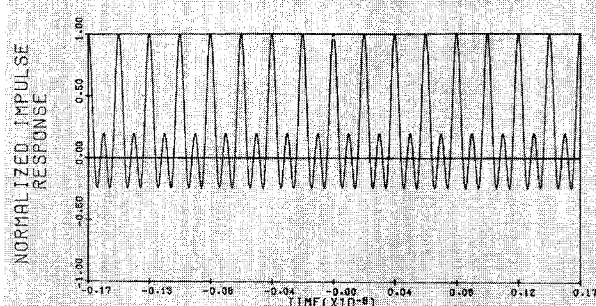


Figure 5a. (top) Transducer needed to implement tree filter. Results from sampling time time function of Fig 4b. Shown are center "tap" and right-half of transducer only.

Figure 5b. (bottom) Filter frequency response with input and output transducers corresponding to above. Material: YZ $LiTaO_3$. Linewidth and gap spacings: 0.7436μm.





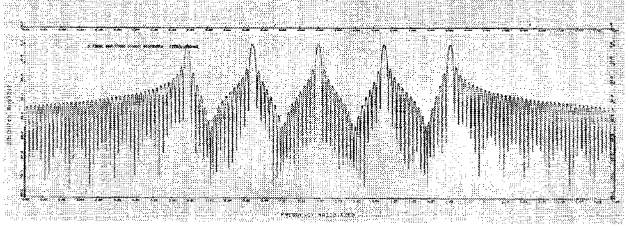


Figure 6a. (top) Frequency response to be realized.
Figure 6b. (center) Illustration of the baseband time response used to realize the above frequency response.
Figure 6c. (bottom) Ideal frequency response of single transducer having finger overlap values determined from equation (13).