TAPPED-LINE INTERDIGITAL FILTER EQUIVALENT CIRCUITS

Christoph Ernst and Vasil Postoyalko

Department of Electronic and Electrical Engineering, University of Leeds,
Leeds LS2 9JT, England

ABSTRACT

An exact equivalent circuit for the tapped-line interdigital filter geometry is deduced from an exact equivalent circuit of multiple-coupled lines. For a third order filter an analytical expression of the insertion loss function was obtained and compared to the one computed from Cristal's [1] proposed exact equivalent circuit. Cristal's circuit behaved considerably different in the stopband and in particular it does not predict the transmission zero closest to the passband.

INTRODUCTION

Multiple coupled transmission line structures are one of the most attractive filter networks, since they offer a very compact realization of the insertion loss function. A tapped-line filter configuration is sketched in Fig. 1. In the synthesis only adjacent coupling is assumed by Cristal. His proposed equivalent circuit representation usually is the starting point for the design of these types of filters (Fig. 2). The element values y_{ab} , a,b=1,2,3 are the entries in the admittance matrix and represent a characteristic admittance y_{ab} of an isolated transmission line or an isolated short circuited stub. Caspi et al [2] further simplified Cristal's circuit and evaluated analytical design equations. Researchers like Carl Denig [3], who published designs of tapped-line interdigital filters in inhomogeneous media, rely on Cristal's network.

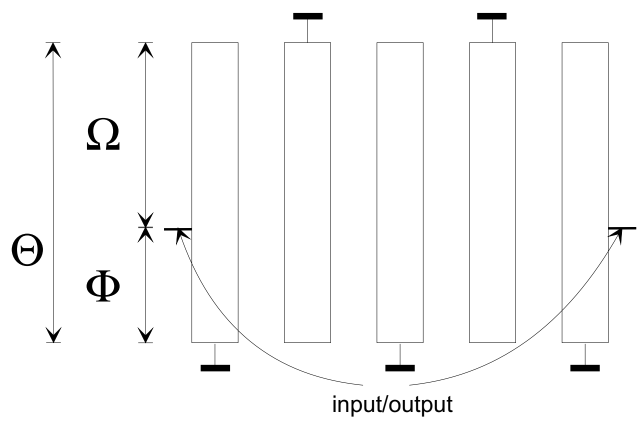

Figure 1: Sketch of fifth degree multiple-coupled tapped-line filter

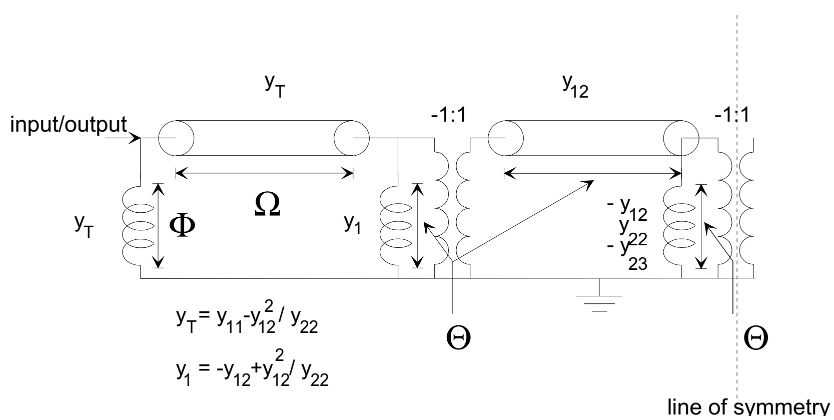

Figure 2: Cristal's claimed exact equivalent circuit for a 3rd order symmetrical tapped-line interdigital filter

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EXACT EQUIVALENT CIRCUIT

An exact equivalent circuit for the tapped-line filter may be evaluated from the admittance matrix of n multiple coupled lines [4].

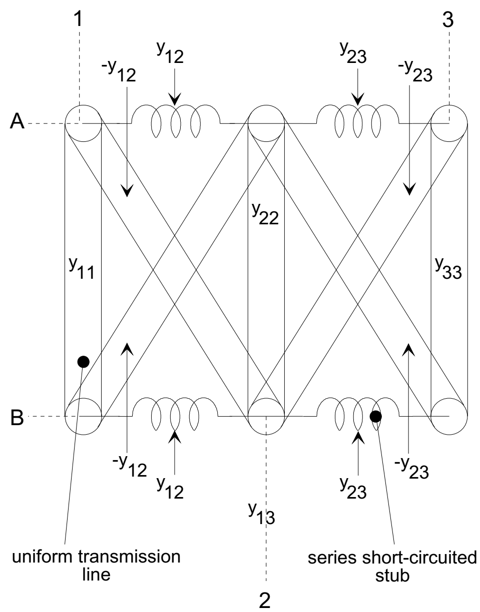

Figure 3: Exact electrical model of three coupled lines when nonadjacent coupling is neglected

For three coupled lines, when nonadjacent coupling is neglected, the exact equivalent circuit is illustrated in Fig. 3. By open-circuiting nodes 1,2,3 and short-circuiting all others in Fig. 3 the well known equivalent circuit of the end-fed interdigital filter would result.

Exact equivalent circuits of symmetrical odd-degree tapped-line interdigital filters are obtained when two multiple-coupled line blocks are joined together as illustrated in Fig. 4.

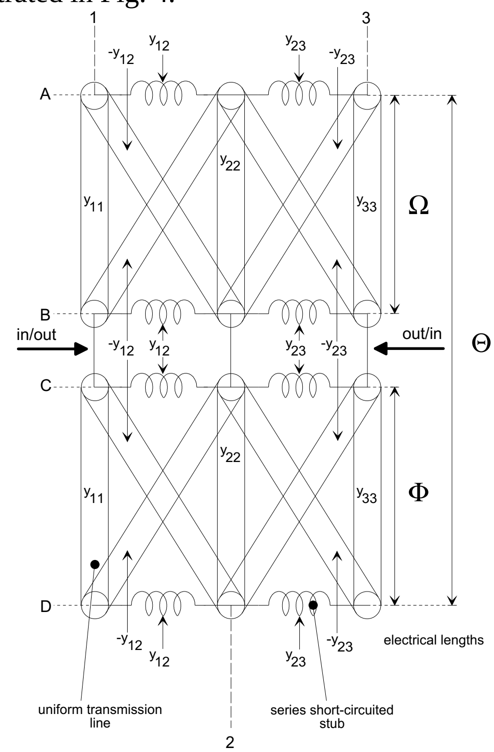

Figure 4: Electrical network of tapped-line interdigital prototype of 3rd degree, nonadjacent coupling neglected

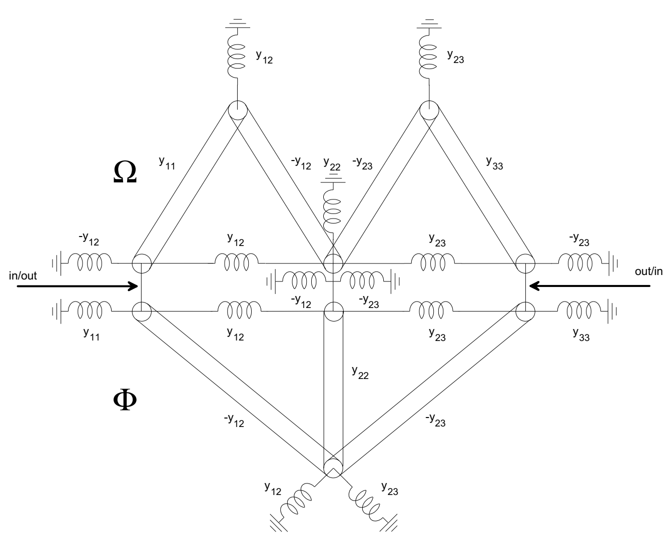

Figure 5: Exact equivalent electrical network of a 3rd degree tapped-line interdigital filter

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Applying the boundary conditions, the network shown in Fig. 5 results. Symmetrical even-degree tapped-line filters require three multiple-coupled line blocks.
Cristal suggested graph-transformations [5] to simplify a tapped two-coupled line structure, from which he deduced a circuit for tapped n-coupled lines, but he does not explicitly present the derivation of his general circuit.
Using his proposed circuit and the exact one, the computed insertion loss function is illustrated in Fig. 6 for a symmetrical 3rd degree, 20% bandwidth tapped-line interdigital filter. The input/output-tapping compensating capacitance (Cap) [1, 2] was included in both circuits.

Good agreement can be observed in the passband, whereas the stopband-performance is completely different.
In particular, the transmission zero close to the passband is not predicted by Cristal's circuit, nor is it due to the effect of nonadjacent coupling since nonadjacent coupling is neglected in the analysis. Instead, Cristal's circuit exhibits transmission zeros when the short circuited stubs of electrical length Θ and Φ become quarter of a wavelength ($f_{\Theta,zero}$ = 3GHz and $f_{\Phi,zero}$ = 10.771GHz (not shown)).

In order to gain some insight in the behavior of tapped-line interdigital filters, the 3rd order tapped coupled line structure in Fig. 5 was analytically examined and an expression of the insertion loss function in the complex variable ($j\omega$) was obtained using the mathematical tool Xmaple:

$$s_{21} = \frac{N_1 N_2}{D}, \qquad (1)$$

where

$N_1 = 2a$,
$N_2 = a^3 p_1(x) + a^2 p_2(x) + a\, p_3(x) + p_4(x)$,
$D = a^3 p_5(x) + a^2 p_6(x) + a\, p_7(x) + p_8(x)$,
$a = \tan(\Phi)$, $b = \tan(\Omega)$,
$p_1 \ldots p_8$ linear combinations of

$x = \{\sqrt{-1}, b, b^2, b^3, \omega, \omega^2, Cap, Cap^2, y_{ij}\}$

The compensating capacitance (Cap) at the open circuit of the first and last resonator was included in the analysis, since this is an important design parameter [1, 2]. Equation (1) is a multivariable function in (ω), $\tan(\Phi(\omega))$ and $\tan(\Omega(\omega))$ which was found to exhibit zeros when

$$\tan(\Phi) = 0 \text{ or} \qquad (2)$$
$$N_2 = 0. \qquad (3)$$

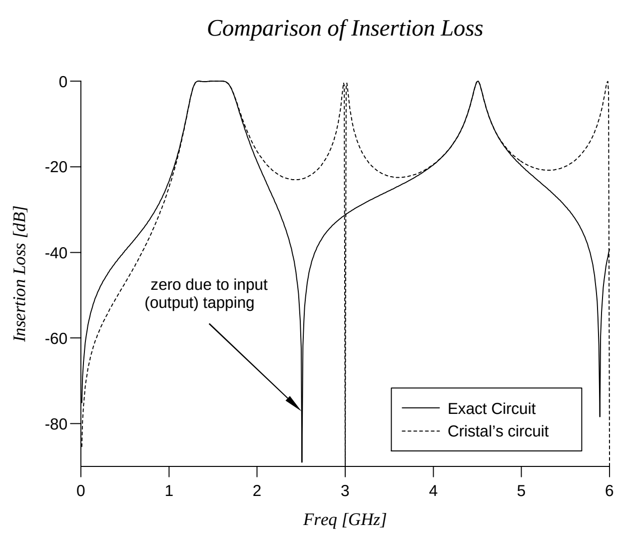

Figure 6: Comparison of the Computed Insertion loss of a 3rd order bandpass filter with f_{centre} = 1.5GHz, 20% BW , 3rd order bandpass filter, using Cristal's network and the exact one

(1) Admittance Matrix
$y_{12} = y_{23} = 0.17748496$
$y_{11} = y_{33} = 1.01081830$
$y_{22} = 1.18830327$
(2)Compensating Capacitance:
Cap = 7.7788 pF*Ohm
(3) Overall Resonator Length:
l = 49.97 mm
(4) Tapping Point Distance:
l_t = 15.31 mm

Table 1: Normalized element values of tapped-line filter in Figure 6.

It is interesting to note that the short circuited stub of electrical length (Ω) with negative characteristic admittance ($-y_{12}$) at the input/output node does not produce any transmission zeros, nor does the other short circuited stub ($f_{\Phi,zero}$) produce the one closest to the passband:

$$f_{\Phi,zero} = k\frac{c_0}{2l_t}, \; k \in Z,$$

c_0 speed of light,
l_t the tapping point distance.

In practical designs $l_t << l$, (l) being the overall resonator length, hence

$$f_{\Phi,zero} >> f_{centre}.$$

This leaves (N_2) only to produce the transmission zero closest to the passband, but (N_2) being a highly nonlinear function in (ω), no analytical solution could be obtained. However, numerically solving equation (3) for the filter in Fig. 6 the location of the transmission-zero closest to the passband was found to be at 2.511GHz, which agreed with simulations using MIRCOWAVE HARMONICA PC.
Setting Cap = 0, an analytical expression for $N_2 \neq 0$ was evaluated and solved (f_{zero} = 2.642 GHz) in order to verify, that the capacitance is not the reason for the transmission zero. Indeed, it was observed, that *all* parameters defining the filter structure, i.e. l, l_t, y_{ab} (a,b = 1..3), contribute to its location.

CONCLUSION

It has been shown that the commonly used electrical network representation for tapped-line interdigital filters as proposed by Cristal fails to predict the insertion loss function produced by a third order degree filter. This suggests that Cristal's proposed equivalent circuit for n-degree tapped-line filters [1] is wrong. However, it still remains useful to obtain approximate element values of these type of filters.
Furthermore, it is explicitly shown, how to obtain an exact equivalent circuit for a 3rd degree symmetrical tapped-line filter. Using the same principles, higher odd-degrees symmetrical filters could be modeled. Unsymmetrical tapped-line filters or symmetrical even degree ones require three or more than three multiple-coupled line blocks.
Symmetrical three resonator filters were analysed analytically. Tapping the input/output line was observed to produce a transmission zero close to the passband, the location of which was dependent on all parameters defining the filter, i.e. overall length (l), tapping point distance (l_t) and the characteristic admittances y_{ab} (a,b = 1..3).

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