A 16 TAP HYBRID PROGRAMMABLE TRANSVERSAL FILTER USING MONOLITHIC GaAs DUAL-GATE FET ARRAY

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ABSTRACT

A hybrid programmable transversal filter (HPTF) is described that employs a $LiNbO_3$ SAW delay line and two monolithic dual-gate GaAs FET arrays to control magnitude and sign of the 16 tap weights. The HPTF is completely programmable and is constrained only by the bandwidth (100 MHz centered at 250 MHz) and the number of taps. Theoretical calculations of tap weight control range and dynamic range are presented, compared with experiment and used to justify the hybrid $LiNbO_3$ SAW - GaAs FET combination. A dynamic range of 85 dB and a continuously variable tap weight control range of 70 dB are demonstrated.

INTRODUCTION

The HPTF is an extremely versatile wideband signal processor. This single device can operate as a bandpass, band-reject, adaptable or matched filter [1].

Several programmable SAW filters have been reported in the literature. Most are used for matched filter operation in which ON-OFF ratios of 20 dB are acceptable [2-5]. Recently a SAW/FET approach demonstrated 50 MHz of bandwidth centered at 150 MHz. However, tap control range was limited to 16 dB and single tap insertion loss was 80 dB [6]. A monolithic GaAs approach in which the SAW and the FETs are implemented on the same substrate has demonstrated 58 dB dynamic range at 500 MHz over a 50 MHz bandwidth (10%) [7].

The HPTF described herein has demonstrated 70 dB of tap weight control range. Single tap insertion loss is only 26 dB over a 100 MHz bandwidth (40%) centered at 250 MHz. And dynamic range is 85 dB over the full 100 MHz bandwidth. This combination of SAW technology with GaAs monolithic circuitry is an ideal solution for complex, low loss, programmable signal processing tasks.

CONCEPT

The HPTF consists of a tapped SAW delay line whose output electrodes are connected to an array of tap weight control dual-gate FETs (Figure 1). The signal is applied to an input transducer, which

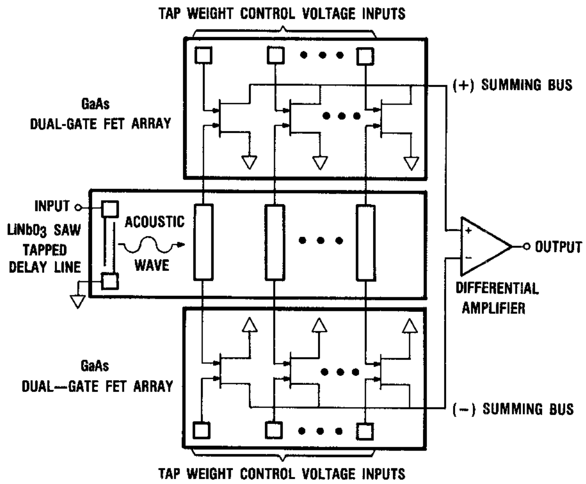

Figure 1. Hybrid Programmable Transversal Filter (HPTF) concept.

generates a surface acoustic wave that propagates down the substrate. An array of output transducers transform this acoustic wave back into electrical signals that are delayed copies of the original input. Each output transducer is connected to the input (gate-1) of a dual-gate FET (DGFET) tap weight control amplifier. The tap weight is controlled by gate-2 voltage. The DGFET outputs (drains) are connected to a common current summing bus. The transversal filter can now be identified by the process of shift, mulitiply and sum. Negative tap weights are generated with a second DGFET array whose output is inverted by an external differential amplifier. This alleviates the need for an inverter at each tap.

ANALYSIS

Poor tap weight control range and poor dynamic range have severely impaired performance of all PTFs reported to date [2-7]. Tap weight control range limits filter sidelobe performance. Low dynamic range nullifies all the advantages of even the best sidelobe performance.

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Dual-Gate FET Model. A simple DGFET small signal and noise model is needed to analyze tap weight control range and dynamic range (Figure 2). Gain control is modeled by the variable transconductance (G_m) and is plotted in Figure 3. DGFET noise is modeled with a white noise current source (I_{dn}) across the drain and source terminals. Normalized noise power $(I_{dn}/I_{dnmax})^2$ is also plotted in Figure 3. Notice that noise power decreases only slightly as gain is decreased. The input capacitance (C_{gs}) is independent of gain control. And knowledge of the output impedance is not needed for this analysis.

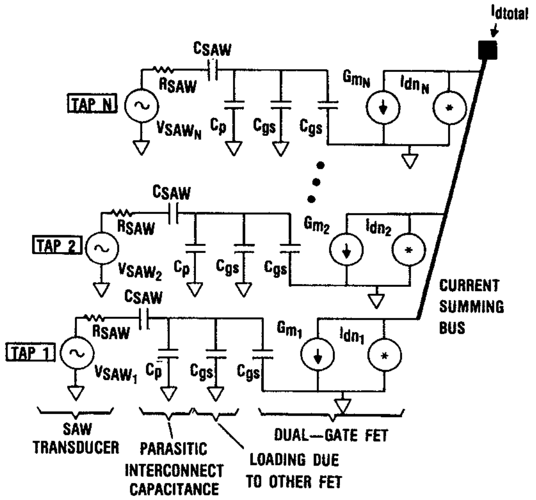

Figure 2. HPTF small-signal and noise model.

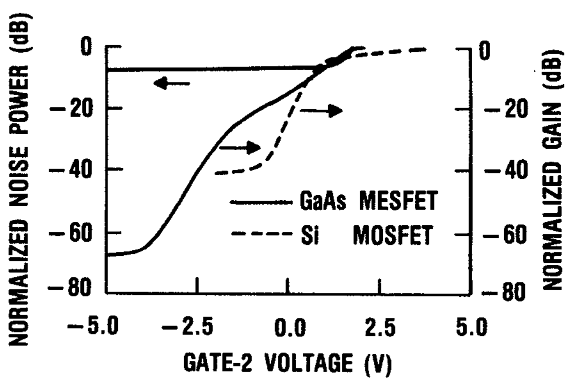

Figure 3. Dual-gate FET gain (G_m/G_{mmax}) and output noise power $(I_{dn}/I_{dnmax})^2$.

Tap Weight Control Range. Tap weight control range is defined as the ratio between the tap amplifier maximum and minimum gains. In Figure 3 the GaAs DGFET is shown to have a 70 dB gain control range. Notice that even the Si DGFET has a gain control range of 40 dB, which far exceeds that of any other approach reported in the literature.

PTF Dynamic Range Analysis. Dynamic range (DR) is defined as the maximum output power at which the filter can operate divided by the filter's output noise power. The maximum power is limited by the power that can be safely applied to the SAW input transducer (about +20 dBm) and by insertion loss. The noise power is dominated by noise generated in the FETs.

Using the model shown in Figure 2, the equation for dynamic range is calculated to be:

$$DR = DR_{max} \left| \text{SAW TO FET MATCHING LOSS} \right|^{-1} \left| \frac{IL}{IL_{min}} \right|^{-1} \left| \frac{Pn}{Pn_{max}} \right|^{-1}$$

SAW and FET material dependence — Cp, Wsaw and Wfet dependence — dependence on tap weight selection

The second term accounts for increased insertion loss due to non-ideal SAW-FET matching and due to parasitic interconnect capacitance. This term describes all dependence on FET gatewidth and SAW beamwidth (since FET input capacitance is proportional to gatewidth and SAW electrode capacitance is proportional to beamwidth). Figure 4 is a plot of this matching term. Matching loss is minimized when $2C_{gs} = C_p + C_{saw}$. However, notice that a factor of five deviation from the optimum FET to SAW capacitance ratio results in less than 3 dB degradation in dynamic range. Furthermore, less than 4 dB degradation results for a parasitic interconnect capacitance (C_p) equal to Csaw.

Insertion loss increases when the filter is programmed to a center frequency other than F_{samp} because some of the required tap weights are less than unity and all taps are not in phase (third term); output noise power decreases because of the tap weights that are less than unity (fourth term). However, insertion loss always increases faster than noise power decreases (see Figure 3). So, the third and fourth terms describe the degradation to dynamic range due to tap weight programming.

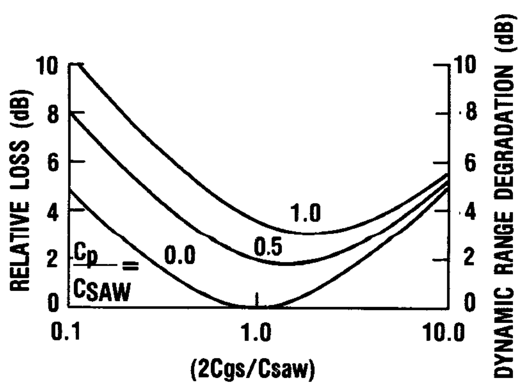

Figure 4. Insertion loss and dynamic range degradation due to non-ideal SAW-FET matching and to parasitic interconnect capacitance (C_p).

DR_{max} is a constant that is independent of FET gatewidth, SAW beamwidth and filter programming. DR_{max} incorporates all of the material and process dependent parameters. DR_{max} is the dynamic range (DR) when:

1) $G_m[1...N] = G_{mmax}$,
2) $F = F_{samp}$ (all taps are in phase),
3) $C_{saw} = 2\,C_{gs}$ (optimum FET - SAW matching),
4) $C_p = 0$ (no parasitic capacitance).

$$DR_{max} = \frac{N}{4F\,BW}\;\underbrace{\frac{F_t\;G_{mmax}}{I_{dnmax}^{2}}}_{\text{FET material dependence}}\;\underbrace{\frac{P_{inmax}}{Q_{saw}\;IL_{in}}}_{\text{SAW material dependence}}$$

Where:

- BW = total device bandwidth (for noise calculation)
- G_{mmax} = transconductance at maximum gain setting
- F = signal frequency
- F_t = frequency at which FET current gain becomes unity ($G_{mmax} / (2\pi C_{gs})$)
- I_{dnmax} = FET output noise current at maximum gain setting
- IL_{in} = insertion loss of input transducer (when matched to cover the full bandwidth)
- N = number of taps
- P_{inmax} = maximum operating power of SAW input transducer (+20 dBm)
- Q_{saw} = output transducer Q ($R_{saw}\,C_{saw}\,\omega$).

Several monolithic GaAs approaches were considered (see Table 1). GaAs has a very low piezoelectric coupling coefficient (very large Q_{saw}). Signal level on the output transducer is proportional to this coupling coefficient. Q_{saw} accounts for this effect in the DR_{max} equation. Since the low coupling cofficient also results in very high input transducer Q, large mismatch loss must be accepted on the input transducer to achieve the 100 MHz bandwidth. An edge bonded input transducer [6] improves insertion loss (IL_{in}) and DR_{max} by 8 dB. A thin (0.04 wavelength) ZnO film on the GaAs surface under the input transducer [7] increases the coupling coefficient, which improves IL_{in} and dynamic range by 13 dB.

Two hybrid versions were also analyzed and were fabricated (see Table 1). The GaAs FET - $LiNbO_3$ combination exhibits the highest dynamic range due to the high piezoelectric coupling SAW substrate and the high F_t of its FETs. The Si FET version [8] exhibits a 10 dB lower DR_{max} due to the lower F_t of its FETs.

Ideally, dynamic range equals DR_{max} when all taps are programmed to unity. DR is degraded by parasitic interconnect capacitance (C_p) and non-ideal SAW to FET matching in the experimental hybrid versions. Ideally, DR decreases by 16 dB when only one tap is on (24 dB gain decrease, 6 dB noise decrease, 2 dB DR_{max} increase).

Table 1. Dynamic Range for Several PTF Designs.

PTF DESIGN	DRmax (dB) F = 200MHz	DR (dB) single tap on F = 250MHz	DR (dB) all taps on F = 200MHz
Monolithic GaAs:			
standard transducers	66	50	66
$LiNbO_3$ edge bonded input transducer [6]	74	58	74
ZnO overlay [7]	79	63	79
Hybrid, $LiNbO_3$ SAW:			
discrete Si MOSFETs [8]	92	68 <70>	83 <76>
monolithic GaAs MESFET array	102	81 <77>	97 <85>

< > = MEASURED

DESIGN

Figure 5 is a photograph of the GaAs DGFET array chip. 50 µm was chosen for the DGFET gatewidth as a trade between dynamic range degradation (2dB) and power dissipation (about 50 mW per tap). Two identical GaAs DGFET arrays (one for positive and one for negative tap weights) were wire bonded to the SAW device. Negative tap weights were generated by an external differential amplifier. The 32 gate-2 tap weight voltages are controlled by external D/As. Drain current is supplied through an RF choke. No output matching was attempted.

Figure 6 is a photograph of the experimental PTF. A 250 MHz center frequency, three wavelength long interdigital transducer launches the acoustic wave. Two such transducers were patterned on the substrate for characterization. A beamwidth of 75 lambda was chosen to facilitate matching. This transducer is excited by a balanced hybrid through two matching inductors. The balanced drive minimizes electromagnetic coupling to the FET inputs.

The acoustic wave is detected by an array of sixteen quarter wavelength (at 200 MHz) active electrodes interleaved with grounded electrodes. The active electrodes fanout to bond pads on both sides of the chip. The fanout contributes about 300 fF of parasitic capacitance, which degrades dynamic range by about 3 dB.

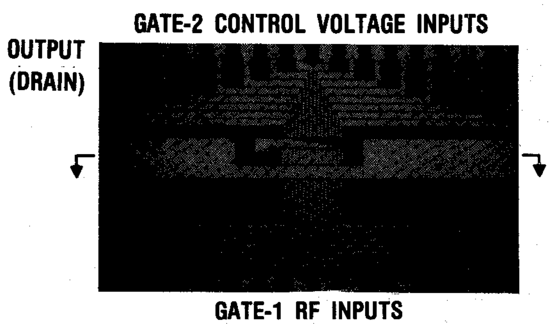

Figure 5. Photograph of the 16 tap GaAs DGFET array chip.

EXPERIMENTAL PERFORMANCE

Figure 7 is a photograph of the single tap response. Midband insertion loss is 26 dB (theory predicts 28 dB). Figure 8 is a photograph of the response with all taps on. Insertion loss is 10 dB at 200 MHz (theory predicts 7 dB). The response with all taps off is also shown in Figure 8. All 16 FETs contribute equally to the response when all taps are off. So the response should have the same shape as the response with all taps on. And the difference in gain is the tap weight control range. Figure 8 shows the tap weight control range to be 70 dB.

Dynamic range is the ratio of maximum output signal power to output noise power. Maximum output signal power is limited by insertion loss and the power that can be applied to the input transducer (+20 dBm). Noise power was measured using a precision noise figure meter. With one tap on, noise power was 10.5 dB above KT across the full 100 MHz bandwidth (theory predicts 4.5 dB). And with all taps on, noise power was 19 dB above KT (theory predicts 10.5 dB). Dynamic range is 77 dB with one tap on. Our theory predicts 81 dB. The theory is 2 dB high in insertion loss and 6 dB low in noise power. Dynamic range is 85 dB with all taps on. Our theory predicts 97 dB for this case. The theory is 3 dB low in insertion loss and 9 dB low in noise power.

CONCLUSION

All programmable transversal filter (PTF) designs reported to date are severely limited by poor tap weight control range and poor dynamic range. The hybrid PTF solves both of these problems by combining a $LiNbO_3$ SAW device for high dynamic range with GaAs DGFETs for high tap weight control range. Measured tap weight control range (70 dB) and dynamic range (85 dB) are high enough to meet many system requirements.

ACKNOWLEDGEMENT

This work was supported by the U.S. Air Force Wright Aeronautical Laboratories through the U.S. Air Force Avionics Laboratory under contract F33615-82-C-1859.

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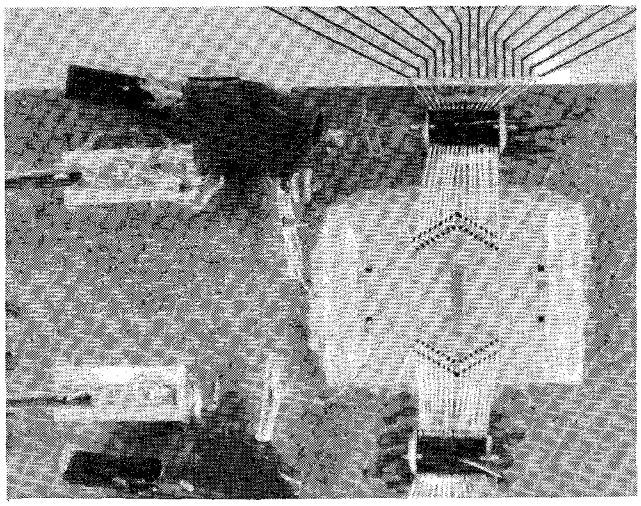

Figure 6. Photograph of the 16 tap HPTF.

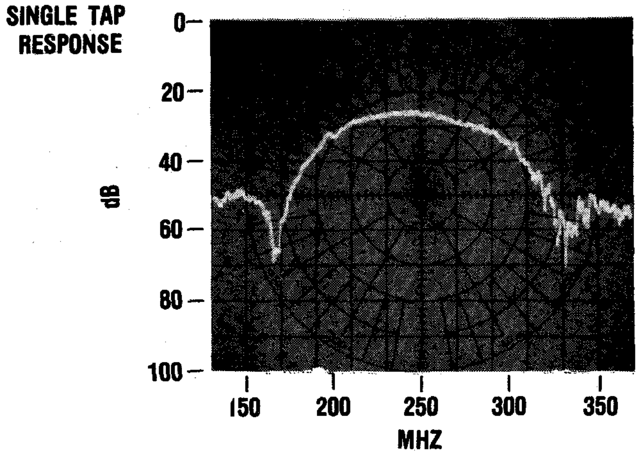

Figure 7. HPTF frequency response with only one tap on. Insertion loss is 26 dB.

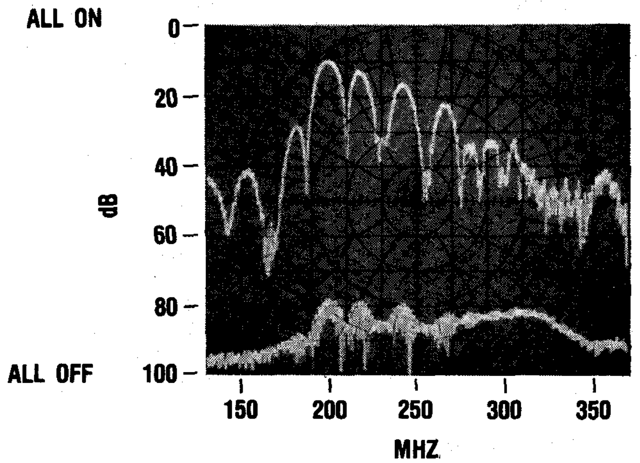

Figure 8. HPTF frequency response with all taps on and with all taps off. Tap weight control range is 70dB.