Performance analysis of adaptive transversal filters for high-speed lightwave systems

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Abstract: The analysis of transversal filters based on a novel cell design in common-source configuration (TF-CS) is presented. Based on this approach, a distributed transversal filter was designed as a monolithic microwave integrated circuit (MMIC) for optical-CDMA receiver systems [1]. In order to assess its performance, a transversal filter based on Gilbert cells (TF-GC) was designed using the same HEMT process. Analyses of both transversal filters allow comparing their performance in terms of gain, bandwidth and noise behaviour. Simulation results support our conclusions in favour of the novel approach.

1 Introduction

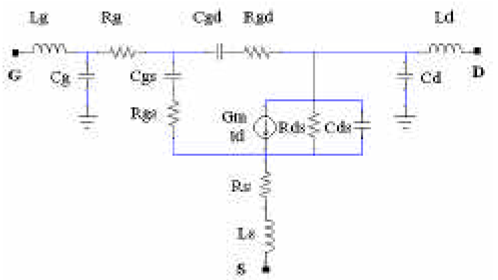
Post-detection filters play an important role in high-speed optical communication systems. Adaptive transversal filter allows tuning the receiver to compensate optical link distortions and receiver non ideal responses. Transversal filters have been designed as post-detection filters to signal shaping previous to the decision device. Moreira *et al* [1] presented a technique to achieve amplification and filtering in the same structure using distributed amplification principles. Borjak *et al* [2] established the analogy between transversal filters and distributed amplifier topologies. The transversal filter concept was established by portioning the gain into distributed cells using active devices with different geometries so as to tailor the filter response [1, 2].

Adaptive filters have been also constructed using distributed principles. In such filters, tap weights are actively tuned by changing voltage biases applied to active devices. MMIC adaptive transversal filters are easily reconfigurable and provide different functions such as pulse shaping, phase shifting and automatic gain control [4]. Based on the bias tuning technique, adaptive filters have been implemented as tuneable post-detection filters [3] and transversal adaptive equalisers [4]. Recently, a transversal filter based on a novel cell design was implemented as a MMIC for optical CDMA receiving systems [1]. The filter features positive and negative tap gain control which improves the reception of CDMA signals.

In this paper, the performance of transversal filters with bipolar capacity based on Gilbert cells (TF-GC) [4] and transversal filter based on active device in common mode configuration (TF-CS) [1] are compared using a fully-characterised HEMT process.

2 HEMT process modelling

A commercially available pseudomorphic-HEMT process with a 0.2 µm gate length was characterised using microwave circuit optimisation techniques and the small-signal equivalent model of the device shown in Fig 1. The extracted values are in excellent agreement with the model of the process over a wide range of frequencies. This model was used in MMIC designs. The active device is based on (Ga , Al) As-(Ga , In) As-GaAs heterostructure with triangular gate profile. The current cut-off frequency is equal to 57.8 GHz



Gm = 643 mS/mm	Cgs = 980 fF/mm
Cgd = 160 fF/mm	Rgs =0.14 Ω.mm
Cds = 228 fF/mm	Rgd = 1.04 Ω.mm
Rds = 25.86 Ω.mm	td = 0 ps

Fig 1 Small signal model and intrinsic element values scaled to gate width (Vds=3.0 V and Vgs=0 V)

It is worth noticing from the model of Fig 1 that the capacitance ratio Cgs/Cgd is equal to 6.1, which is particularly low when compared to conventional HEMT structures [7]. In addition, the series resistance in the source terminal Rs (equal to 0.54 Ω.mm) reduces the effective transconductance of the active device to 478mS/mm. Losses associated to the active device reduces the effective gain of filter distributed cells.

2 TF based on amplifying cells in common source configuration [1]

The transversal filter topology and the equivalent model for transmission lines sections are shown in Figure 2. It differs from other topologies described in the open literature [2-4] in that the filter consists of two rows of active devices sharing a common gate artificial transmission line. Each row has a separate drain artificial transmission line. The symmetry of the structure ensures that there is no signal at the output port when each pair of active devices in both lines has the same gain; the same input voltage is applied to each pair of active devices.

The lumped representation of Fig 2 provides an insight into the sections of the resulting artificial transmission lines (ATL). The voltage in the node of the common gate section is actively coupled to both external transmission lines via controlled current sources. Traveling-waves in the common transmission line are amplified by transconductances and coupled to external transmission lines. Signal components in each transmission line travel in opposite directions towards terminal resistances. The counter propagating components are of interest since the filter structure introduces the necessary signal delay while using short transmission lines in MMIC implementations [1, 2]. The phase inverter allows signals from both external rows to be summed in anti-phase.

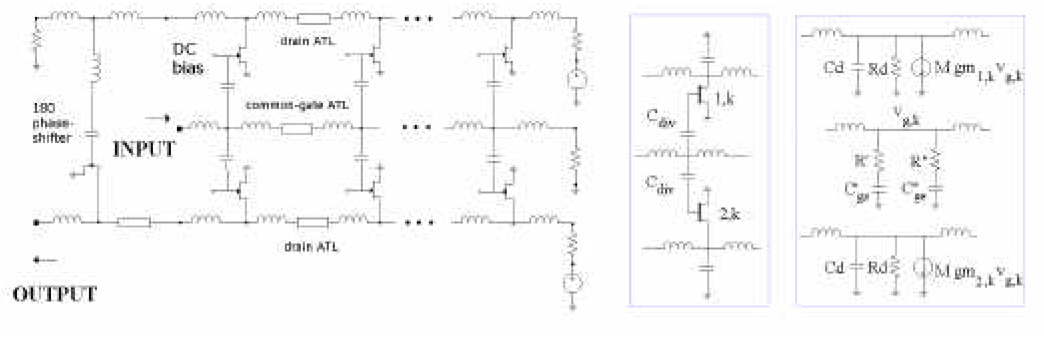


Fig 2 Adaptive transversal filter, distributed amplifying cell and lumped equivalent model

Using the theory of transversal distributed filters [2], it is possible to arrive to the transfer function of the structure given by:

$$H_F(jw) = \sum_{k=1}^{N} G_K \exp\left(-jw\sum_{i=0}^{k-1} t_i\right) \qquad [1]$$

where t_k corresponds to tap delay, equal to the bit period; and $|G_k|$ is the tap weights given by:

$$G_K = M \times (g_{2,k} - g_{1,k}) \qquad [2]$$

The proportionality factor *M* is related to the voltage division of series capacitance, C_{div} with the device input capacitance. We deemed appropriate the use of series capacitances of the order of the cell capacitance, C_{gs} , so as to reduce the effect of losses of the active devices and maintain pulse shape integrity [1]. This capacitive coupling technique permits distributed circuit frequency to be boosted in spans of multi-octave bandwidths [6]. The *M* factor can be well-approximated for any control voltage [5] by the equation

$$M = \frac{C_{div}}{C_{div} + C_{gs}} \qquad [3]$$

The authors envisaged an active matching technique in the common transmission line [1, 5] by which the capacitance per cell is maintained constant while the effective gain of the cell can be adjusted from a maximum to a minimum gain. The capacitance per section in the common ATL is given by:

$$C_{gs} = M \times \left(C'_{gs} + C''_{gs}\right) \qquad [4]$$

where C'_{gs} and C''_{gs} are the input capacitance of the HEMTs at two DC control voltages. The cut-off frequency of the transversal filter is adjusted in function of the *M* factor and characteristic impedance $Z_{0,g}$ given by:

$$f_c = \frac{1}{pZ_{o,g}C_{gs}} \qquad [5]$$

3 Comparison with Gilbert-cell based TF

The use of Gilbert cells for transversal filter applications was reported in [4]. In the MMIC implementation, Gilbert cell was used as a controlled-gain amplifier as shown in Fig 3. The upper part of the Gilbert cell is a series connection of source-coupled pairs. Two cross-coupled (emitter-coupled) pairs produce a differential current at the output port controlled by input voltage bias. Positive or negative tap weights can be set to modify the filter response. The internal strong mismatching of the cell between the input stage and the emitter-coupled pair reduces the influence of frequency-dependent impedances and permits amplification in a wide range of frequencies. For transversal filter designs, the input impedance of the cell is designed to 50 O to directly couple the artificial transmission line whereas its high output impedance provides excellent matching conditions at the output ATL.

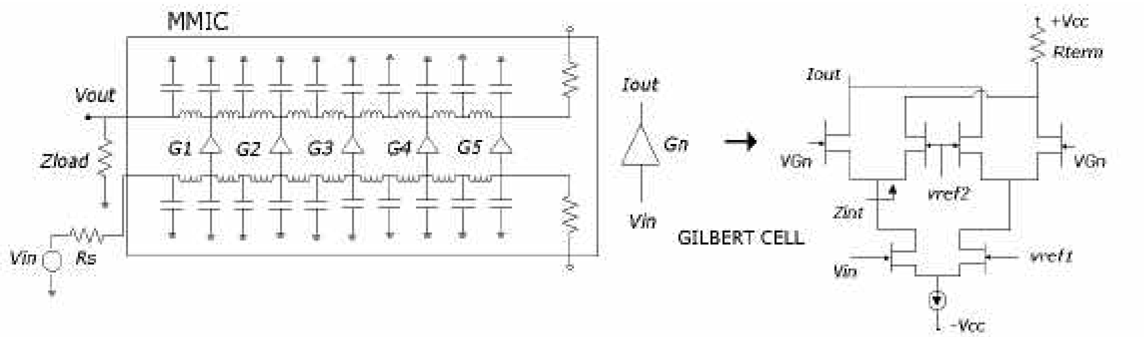


Fig 3 Distributed transversal filter based on Gilbert cells [4]

The gain of cells is obtained in function of the input voltage assuming small signal models of the HEMT process. In the filter design all HEMTs are identical. The cut-off frequency of the transversal filter was 25GHz and mainly limited by the HEMT input capacitance. Simulated results of the gain function of the Gilbert cell is depicted in Figure 4. The transcoductance was scaled to the gate width of HEMT for comparison purposes. It shows a maximum transconductance of about 200 mS/mm which is approximately a half of the maximum extrinsic transconductance of the HEMT (478 mS/mm). The reduction on the gain stems from low internal impedance Z_{int} that is the load of the input (follower) stage. The gain of the Gilbert cell cannot be increased by designing the emitter-coupled pairs with larger HEMT gate widths given that the internal impedance is reduced by the same factor the controlled transconductance is increased.

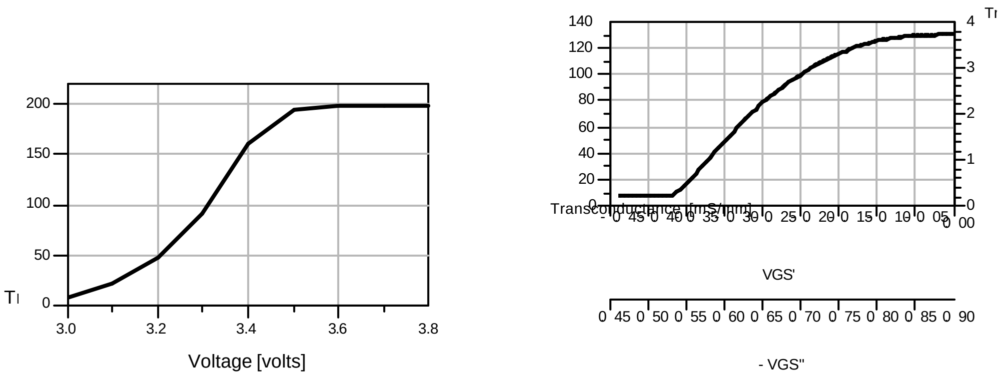


Fig 4 Transconductance and bias current against input voltage of Gilbert cell (left) and CS-cell (right)

Figure 4 also shows simulation results of the CS-cell gain. As it was pointed out earlier, the gain was reduced due to the voltage division of the series capacitance. By using a factor $M = 0.33$, the frequency span was set to 35 GHz which was an aim of the filter design [1]. It is interesting to note that the same gain and bandwidth respect to the TF-GC design could be achieved by increasing the M factor equal to 0.5. The bandwidth-gain product of TF-CS is similar to that usually considered in the design of distributed amplifiers and heavily depends on the characteristics of the process [5].

The use of the input capacitance to couple the active device has as a main drawback a reduction on the cell gain near DC frequencies [6]. In this technique, the voltage division with series capacitance is not ideal since the input resistance of the active device reduces the voltage coupled to the active device at low frequencies. The low cut-off frequency of the filter was 1.8 MHz, which gives a transversal filter with more than 4-decade- BW. This is a figure usually required by standard lightwave systems. In contrast, TF-GC design does not present capacitance in the signal path and DC signal conditioning is feasible; however Gilbert cells require larger bias voltages and physical limitations of transmission lines impose a constraint on the number of cells in MMICs.

Noise analyses were carried out using noise current sources that models the HEMT process. In both cases, the gain weights of filter were adjusted to their maximum value. Simulation results given in Figure 5 reflect to some extent the level of complexity of both distributed cells. Lower densities noise currents of TF-CS is a result of performing the signal inversion which partially eliminates correlated current components of both external transmission lines [5]. The noise performance can be improved in the TF-CS design [5].

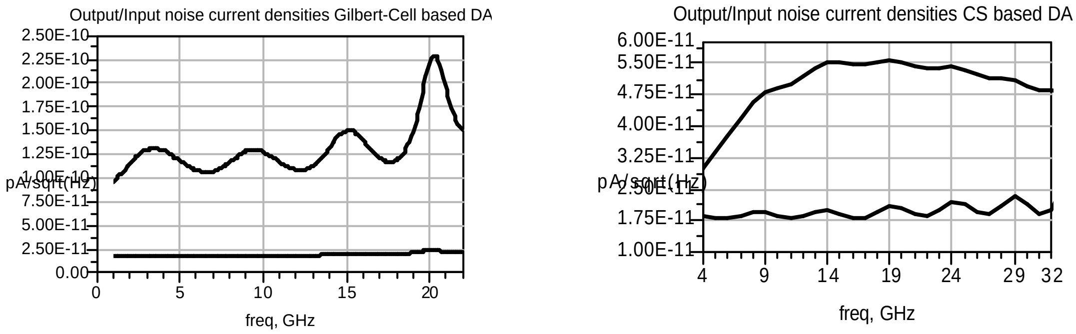


Fig 5 Simulated input and output noise current densities for TF-GC (left) and TF-CS (right)

4 Conclusions

The performances of two transversal filters implemented as MMIC [1, 4] with the same functional capacities have been analysed. TF-CS present advanced performance characteristics. It permits low complexity in the implementation, larger bandwidths and lower noise performance and offers the possibility of increasing the gain of the cell by using an improved HEMT process. Conversely, Gilbert cells can be directly coupled to transmission lines featuring DC amplification; however it presents more complexity in the design and reduced margin to optimise the filter performance. A 7-tap transversal filter based on the common-source cell design is to be sent to fabrication

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