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RESUMEN DE TESIS DOCTORAL / Ph. D THESIS ABSTRACT

Transversal Filter MMIC design for Multi-Gbit/s Optical CDMA Systems

*Diseño de Filtro Transversal Monolítico Integrado de Microondas (MMIC)
para los Sistemas Ópticos CDMA en el Régimen de Multi-Gbits/s*

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Abstract

In this work, the approach of the distributed transversal filter for Optical CDMA systems is addressed. It demonstrates that pulse generation and correlation functions can be accomplished in the electrical domain for multi-Gbit/s systems. The practicalities of the approach were assessed using a state of the art GaAs MMIC process. A innovate transversal filter, which is termed the *dual drain-line transversal filter*, was proposed and designed for speed operations exceeding 40 Gbit/s. A new tap gain weight control technique was designed for the proposed topology so that the filter can be modelled with constant distributed characteristics. A framework based on mixed-mode scattering parameters was derived to investigate the various frequency responses of the filter. Similarly, time domain results based on the full parameters of the MMIC design proves the efficacy of the approach. The filter satisfies the first Nyquist criterion and is suitable for multi-Gbit/s CDMA systems.

Keywords: Fibre Networks, Optical-CDMA Systems, Distributed Amplifiers, HEMTs, Transversal Filter, GaAs MMICs

Resumen

Este trabajo de tesis estudia la aplicación de filtros transversales utilizando la técnica de CDMA para los sistemas ópticos de alta velocidad. Se demuestra prácticamente que funciones tales como generación de pulsos y correlación se pueden llevar a cabo utilizando circuitos electrónicos. La viabilidad de estos desarrollos se comprobó mediante el diseño de un circuito monolítico integrado de microondas (MMIC) basado en un proceso comercial de arseniuro de galio (GaAs). Un filtro transversal no reportado con anterioridad, el cual se le denomina filtro transversal con líneas de drenaje dual, fue propuesto y diseñando para velocidades de operación mayores a 40 Gbit/s. Una nueva técnica de control de coeficientes del filtro se diseñó para la topología propuesta de tal forma que el filtro puede ser modelado con características de circuito distribuido constantes. Una estructura de análisis, el cual se basa en parámetros de dispersión de modos mezclados, fue derivada para investigar las diferentes respuestas en frecuencia de la estructura. Similarmente, resultados en el dominio del tiempo que utilizan los parámetros del diseño del circuito integrado muestra la eficiencia de la propuesta. El filtro satisface el primer criterio de Nyquist y es adecuado para sistemas CDMA que trabajan a velocidades de gigabit por segundo.

Palabras Clave: Redes de fibra óptica, Sistemas Ópticos CDMA, Amplificadores Distribuidos, HEMTs (transistores de Alta Movilidad Electrónica), Filtro Transversal, GaAs MMICs (Circuitos de Microondas Monolíticos Integrados de Arseniuro de Galio).

1 Introduction

Multiplexing techniques for fibre networks attempt to access the vast bandwidth of the optical fibre with the aim of including multiple-access capability. Among the multiplexing techniques, Optical Code Division Multiplex Access (OCDMA) has attractive characteristics that make it appropriate for high-speed fibre networks [Mestdagh, 1995]. OCDMA

provides high-speed connectivity, random asynchronous operation and network control simplification. A subtle advantage is the improvement of the compatibility between terminals as the interference effects associated with the non-ideal behaviour of optical devices is reduced. Central to high-speed OCDMA systems is the hardware used to encode and decode data. Since initial developments, *all-optical* implementations were proposed so as to avoid critical bandwidth limitations of electrical devices. Due to its excellent propagation and delay properties, it was recognised that the optical fibre line is well-suited for optical signal-processing [Jackson, *et. al.* 1985; Prucnal, *et.al.* 1986]. Parallel multiplexers based on different fibre optic delay lines have been implemented for *all-optical* multiple access networks [Prucnal, *et.al.* 1986]. Code sequence generators, convolvers and frequency filtering can be implemented using optical delay lines (fibres) as a matter of course. Other popular method for OCDMA systems is the use of fibre gratings to achieve spectral encoding of non-coherent optical sources. In spite of the broadband characteristics of fibre gratings, its use is still incipient given their physical limitations such as temperature dependence, the need of complex and cumbersome external sub-systems and the lack of reproducibility and integration [Fathallah, *et. al.* 1999; Teh, *et.al.*, 2001]. Such disadvantages make fibre gratings unsuited for widespread utilisation in cost-sensitive OCDMA systems.

For non-coherent multi-Gbit/s OCDMA systems there are practical limitations that hinder the implementation of optical networks with a large number of active users. In time domain encoding for use with optical delay lines (such as Optical Orthogonal Coding proposed in [Salehi, 1989]), the number of pseudo-orthogonal codes depends on the length of the processors; as a consequence, the encoders require processors capable of handling femto-second pulses so as to increase the number of channels [Mestdagh, 1995]. Although optical processors of femto-second pulses do exist, those increase greatly the complexity and cost of the network. In addition to practical issues pertaining to the optical processors, there are important sources of noise in the photodetection process of the receivers that affect the reception of CDMA signals. For instance, beat interference, which is directly proportional to the total optical power falling in the photodetector, makes difficult the detection of decoded data since it depends on the aggregate optical signal of all active users [Smith, 1995; Mestdagh, 1995]. The above lead to the consideration that in order to maintain low noise ratios and good performance, practical high-speed OCDMA networks must be designed to accommodate a low number of users. A more efficient approach envisages the combination of the OCDMA technique with Wavelength Division Multiplexing (WDM) technique [Khaleghi, *et. al.* 1995]. That improves the spectral efficiency of the network by creating a set of clusters that shares a CDMA code and each receiver of a cluster responding to a specific wavelength, multiplying effectively the number of available channels.

Initial work in the field of Optical Code Division Multiplex Access (OCDMA) was focused on optical delay-line signal processing. Conversely, electrical components, such as microstrips, were dismissed for such implementation due to the high level of propagation losses and bandwidth limitations [Jackson, *et. al.* 1985]. With the advances in high-speed active device technologies and the sub-millimetre control of transmission lines, signal processing using monolithic microwave integrated circuit (MMIC) is currently a viable alternative. In this work, newly developed MMIC circuits and design strategies are explored for achieving code generation and convolution in the electrical domain. It concentrates on the design, modelling and optimisation of electrical encoders and decoders based on distributed transversal filters. The utility of such electrical encoders rests on their ability to attain high-speed operation. High rate sequences with pulse widths falling in the picosecond region can be handled and filtered electrically. This is illustrated in the block diagram shown in Figure 1 below.

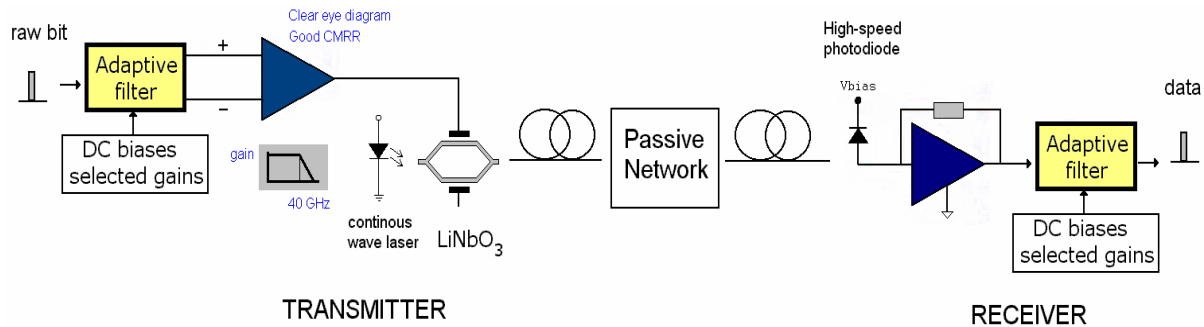


Fig. 1. Transmitter and receiver for non-coherent OCDMA encoding and decoding

The transversal filters in Figure 1 are designed to adapt to a specific code and then used for the generation and detection of OCDMA coded data. External bias voltages allow changing the filter tap gains to a predetermined transmit and receive functions. At the transmitter, user data is encoded in a unique sequence that represents the address of the intentional receiver address. Transmitters must have tuning times of the order of some nanoseconds for encoding user data. Such signals are distributed through a passive network. The filter at the transmitter provides picosecond pulses to a single-ended or two-ended broadband driver; according with the requirements of the external modulator. At the receiver, data are detected non-coherently by the filter which responds to amplitude modulated pulses. When the sequence of the receiver matches with the transmitter sequence, the filter responds with an autocorrelation peak, otherwise, the response is a cross-correlation side lobe. Pulses at the input of the receiver are non-negative and narrow enough so as to not overlap and spread beyond the bit interval.

Different schemes for time domain encoding that lessen the effects associated with the inability to transmit bipolar signals in the optical channel were considered in this work. In particular, versatile and reconfigurable transversal filters that extend filter implementations with positive and negative gain weights were proposed. The bipolar capacity of such filters allows reducing the multiple user interference (MUI) and improves the detection of OCDMA signals [O'Farrell, 1991]. The thesis provides studies of the filters design and performance, identifying the main factors that limit the range of filtering functions and the potential application for lightwave systems.

2 Circuit Design Strategies and Methodology

For OCDMA systems handling pulses in the picosecond region, it is essential to choose circuit topologies capable of satisfying multi-octave bandwidth operations and suitable transient characteristics. One of the techniques well-suited to multi-Gbit/s signal processing is the distributed amplifier. A central development for ultra-broadband circuit design based on distributed amplifier techniques was achieved in [Borjak *et. al*, 1997] by showing that the distributed amplifier and the transversal filter are functionally equivalent topologies. The design of transversal filter based on distributed principles have attractive characteristics for high-speed optical communication systems, such as of providing delay and gain functions in the same structure, excellent monolithic integration capabilities and broadband operation as the bandwidth is limited by the figure of merit of the active device employed. This is traduced in good reliability in fabrication and a reducing the cost associated with large volume production of components [Borjak *et. al*, 1997].

The approach of the analogy between the transversal filter and distributed amplifier is further extended in this work by proposing a novel filter topology that has low complexity in the implementation. The dual-drain line transversal filter topology was proposed to provide bipolar capacity, tuning times of the order of nanoseconds and versatility as a wide variety of filter function can be implemented by adjusting tap gains.

The proposed circuit topology is depicted in Figure 2 and presents the following characteristics:

- The topology consists of N -distributed cells, delay lines between filter sections and an inverter as an output stage. The cell design distributes effectively the parasitic capacitance of active devices in a single input (gate) line and two drain lines.
- External bias voltages applied to gate terminals of HEMTs set the device transconductances thereby adjusting the overall filter function. The cell gain, which can be adjusted continuously from a maximum to minimum value, is defined by the difference between the transconductances of devices of a cell.
- The gate-ATL is shared by two rows of active devices; therefore, different voltage levels applied to active devices (Gate to-Source voltages) may give rise to irregular capacitance loading. A proper tap gain weight control was designed by which the capacitance loading on the gate-ATL is maintained approximately constant in all sections; thereby ensuring uniform transmission characteristics.
- At high frequencies the filter response is diminished as a consequence of having active devices biased at different voltage levels and therefore distinct device cut-off frequencies. Nonetheless, other bandwidth limitations considered in the design process determine the filter bandwidth regardless tap gain adjustment.

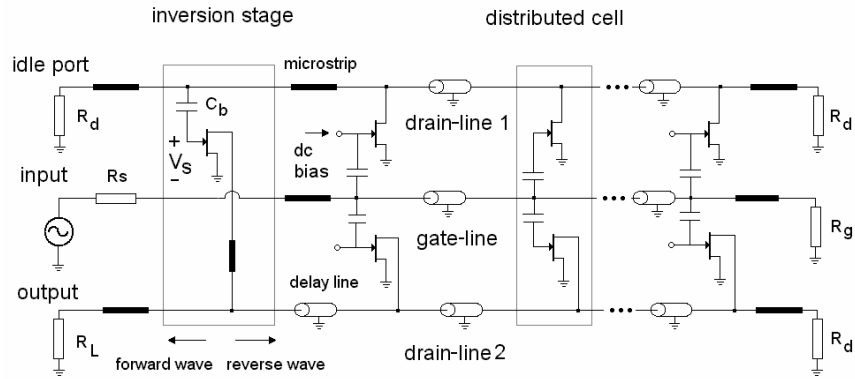


Fig. 2. Schematic of the distributed-amplifier-based transversal filter topology with bipolar capacity

For the filter design, the use of Heterojunction-FETs allowed both suitable matching conditions on artificial transmission lines and high-speed operations. A pseudomorphic-HEMT (PHEMT) with a GaAlAs active layer was used for the design. Figure 3(a) shows the layer structure of the commercially available process employed [OMMIC-Philips Group, 2000]. It is implemented with GaAlAs/GaInAs/GaAs layers grown on a GaAs semi-insulated substrate. The pseudomorphic channel is created by introducing a very thin GaAlAs layer (30Å approximately) with different lattice number from that of the interfacing GaInAs layer. The strained channel of the HEMT increases the effective transconductance while its sub-millimetre gate length (0.2 microns) results in a device with low output conductance.

In the MMIC design, the trade-off between transconductance gain and the inherent bandwidth is determined by the figure of merit of the active device employed. For wideband applications, the device figure-of-merit corresponds to the gain-bandwidth product or also termed the current gain cut-off frequency of the device, f_T . In order for the dual-drain transversal filter to achieve multi-Gbit/s operations, the designer has to consider a linear relationship between the capacitance and transconductance of the device for a wide range of bias voltages, which is consistent with the modelling of practical devices [Anholt, R, 1995]. This active matching condition satisfies the requirement of constant transmission characteristics that ensures minimal pulse dispersion and constant tap delay.

Using circuit simulation and the parameters of the HEMT process, the gain bandwidth product of the HEMT was analysed by extrapolating the values of the current gain at short-circuited output impedance, fitting appropriate transconductance and capacitance values for linear interpolation. The maximum current gain parameter H_{21} against frequency is displayed in a logarithm graph. Figure 3(b) displays the maximum current gain parameter with a 6 dB/octave slope and the extrapolation of the maximum current gain at low frequencies, which indicates in an f_T equal to 66.9 GHz. Although in practical devices, the cut-off frequency varies with applied voltages, other bandwidth limitations set the 3dB point of the filter.

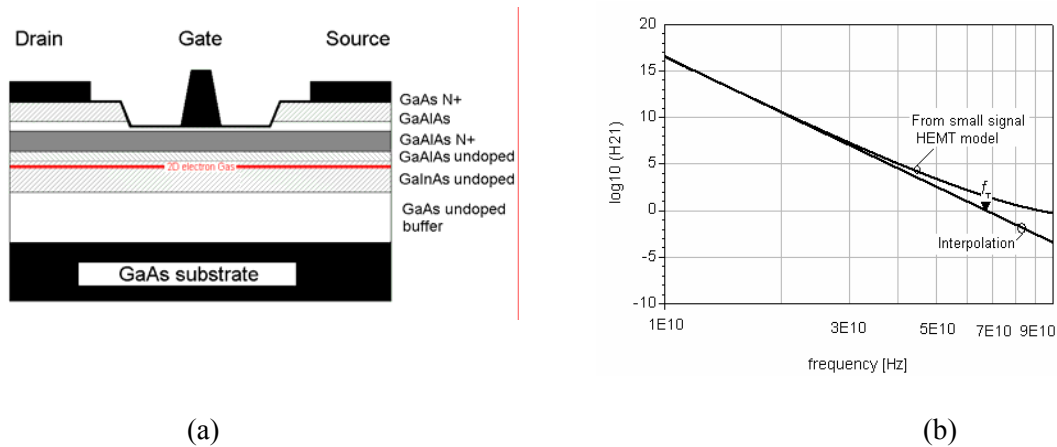


Fig. 3. (a) Epitaxial layer structure of the Pseudomorphic-HEMT process (b) Maximum current gain of a $4 \times 15 \mu\text{m}$ PHEMT for $V_{DS}=3.0\text{V}$ and $V_{GS}=0\text{V}$ (right)

A triple-line transversal filter based on the PHEMT process was designed for speed operations exceeding 40 GChip/s. The performance characteristics of such filter meet the requirements of processors for OCDMA system as outlined above. The design of delay circuits between filter sections (see Figure 1) is of central importance for the transversal filter implementation. The microstrip transmission line was used because of its low losses and broadband operations. Microstrip transmission lines are readily available in the MMIC process based on a GaAs substrate (relative permittivity of 12.9). Such transmission line is surrounded by materials of different permittivities from which its electrical characteristics change with frequency. For filter implementations, microstrip transmission lines introduce an intrinsic time delay as a function of the dielectric constant of the material that confines transversal electromagnetic waves. Short microstrip transmission lines are utilised to interconnect distributed cells constituting an artificial transmission line. Nonetheless, the delay of such artificial line is not sufficient in relation to the width of pulses to be filtered. Transmission lines become unsuitable for multi-Gchip/s MMIC filter implementations as the dielectric constant of practical material is not large enough to slow down transmitted waves. Moreover, the length of transmission lines required to attain the necessary delays makes on chip implementations unfeasible.

The physical length of transmission lines can be effectively reduced by connecting periodically discrete capacitors in shunt with high impedance transmission lines designed to act as distributed inductances; thus passive delay circuits are effectively constructed as low pass LC circuits. The design of microstrip transmission lines acting as inductances has the advantage of reducing the dimensions of transmission lines since the physical length of the lines is decreased in relation to the permittivity of the material in which the line is embedded. In addition, the variation of the permittivity with the frequency has a reduced effect in the characteristic that presents such transmission line when those are implemented as a high characteristic impedance transmission line (typically over 90 Ω) on thick substrates. Considering this practical approach for on chip implementations, the connection of discrete (overlay) capacitors along transmission line involves the use of an ac ground path, which is implemented using via hole. Figure 4(a) shows a schematic of a delay line based on microstrip technology.

The method of design for the filter implementation comprises a trial-analysis-and-redesign process in which different variables that set the filter bandwidth and propagation characteristics were tuned. A redesign stage was done when analysis results did not satisfy initial requirements; circuit simulation and optimisation were performed to compensate for non-idealities of the active device. The implementation of the filter takes into account losses, device parasitics and degeneracies of the MMIC process used. For such aim, external elements and active devices that were tuned, such as blocking capacitors on the gate line, the physical dimensions of the interconnecting transmission lines, terminal impedances and a proper selection of the device gate length.

A transversal filter based on the novel topology was implemented as a MMIC following the rules of the ED02AH process from OMMIC-Philips. The AD02AH process is based on microstrip transmission lines. Figure 4(b) shows a section of the layout of the MMIC. Single-metal layer transmission lines were employed to interconnect discrete elements in gate and drain ATLS. Multi-metal layer transmission lines, on the other hand, were not utilised given the layout restrictions with crossings which are employed to form the dc biasing path of each HEMT. The layout was generated using smart libraries provided by OMMIC and installed in Advanced Design System, ADSTM. The complete filter layout is shown in Figure 5, it was generated from an *equivalent* electrical schematic using the automated tool, resulting in slightly modification of some device parameters or dimensions when necessary. That allows reducing pattern overlap and adjusting devices to be laid out on a grid of 0.5 μm. The chip size is 3.9 × 2.2 mm², within the range recommended by foundry rules.

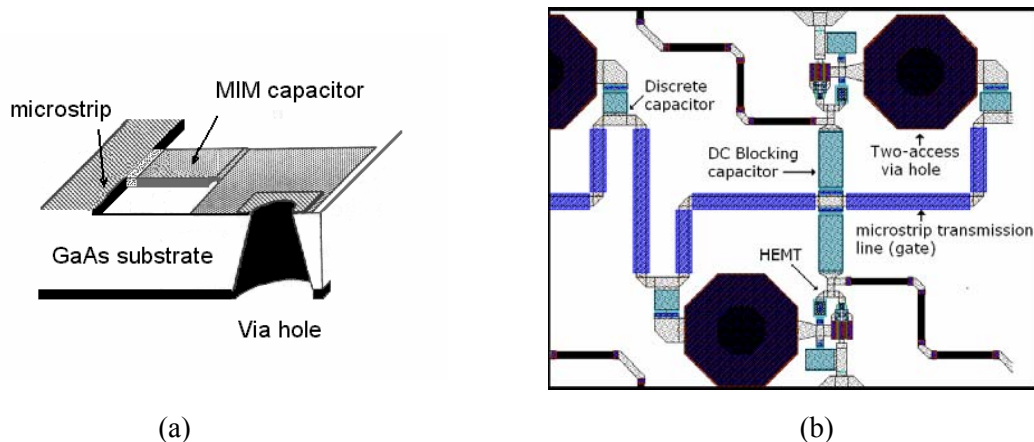


Fig. 4. (a) MMIC implementation of a delay section; (b) A layout section of the MMIC

In the centre of the MMIC pad frame (see Figure 5), the gate line runs horizontally interconnecting overlay capacitors with 90°-bent transmission lines. Vertical lines correspond to thin NiCr resistances which interconnect device gate terminal to bond pads. Each resistance is split at some point so as to introduce crossing with the drain lines. Dry etched via holes were laid out along both sides of gate transmission lines. Overlay capacitors were employed to reduce the length of transmission lines and for blocking DC biases. Microstrip transmission lines in gate and drain lines are designed with different widths (12 μm in drain lines). This allows the biasing of devices in each row up to a maximal current of 78 mA, which is appropriate to avoid metal-migration in microstrips. Two-layer MIM capacitors (based on Silicon Nitride and Silicon dioxide ($\text{Si}_3\text{N}_4+\text{SiO}_2$) as insulator) were synthesised over 60 fF farads taking into account distributed parasitic elements.

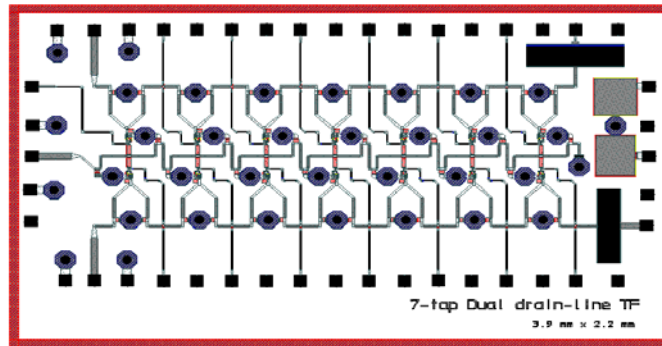


Fig. 5. Layout of the dual drain-line transversal filter with two-ended differential output port

Two-access via hole allows grounding discrete capacitors and HEMTs. The size of via hole is $120 \times 120 \mu\text{m}^2$ and minimum distance between the centres of adjacent via is restricted to $200 \mu\text{m}$. The spacing between horizontal transmission lines and via holes is $70 \mu\text{m}$, this proximity is sufficient to ensure low electromagnetic couplings. The two capacitors of 20 pF (shown in the upper right hand side of the layout) grounded using via hole and connected to bond pads were added for decoupling dc power supply. Bond pads were placed around the chip edge and at least $30 \mu\text{m}$ from the street for dicing. In addition, RF probe pads were added to provide the ground-to-ground connections that are required by conventional probing instruments and aligned with pads according with assembly rules.

3 MMIC Transversal Filter Assessment

The utilization of transversal filter for the reception and generation of high rate sequences was examined using the approach of reciprocal sequences. Potential applications of reciprocal sequences include signal design for optical communication system and testing the optical channel [Al-Dabbagh, *et.al.*, 1998]. Periodical reciprocal sequences present the property of impulsive auto-correlation function and facilitate testing of cascaded transversal filters, in which tap gains are set according to the sequences. Reciprocal multilevel sequences of length 8 were programmed in two transversal filters connected in cascade for testing.

Appropriate bias voltages were applied so as to adjust the transconductance of devices in the distributed cell. To adjust the response of the filter, tap gain compensation was applied so as to reduce the effect of inter pulse interference and attenuation associated with losses of transmission lines. The gain of late filter stages were increased since traveling signals are attenuated in additive fashion along the filter paths. Sharp pulses of 25 ps width were provided at the input of the transmitter, 5 GHz repetition rate of. The transmitter was programmed with tap gains corresponding to the maximal-length (unipolar) sequence (0 1 2 2 0 2 1 1). The filter output, shown in Figure 5, is a 3-level waveform with a period equal to 200 ps, as predicted.

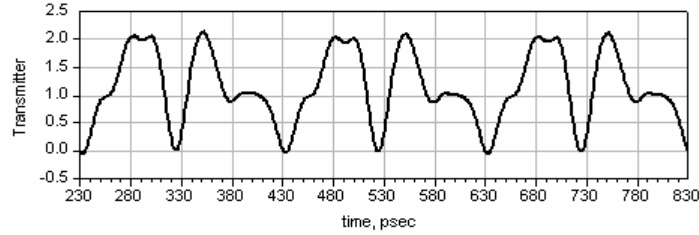


Fig. 6. Periodic response of the transversal filter programmed with multilevel sequence

For testing the transversal filter as a receiver, its gain coefficients were programmed with the (bipolar) reciprocal sequence (-1 -1 -1 +2 -1 +2 +2 -1). Receiver time domain simulations using 25 ps periodic pulses are shown in Fig. 7. For both transmitter and receiver, a very low output oscillatory component is evident. This is a consequence of having low dispersion characteristics in all filter stages and low return losses at the output port of the structure.

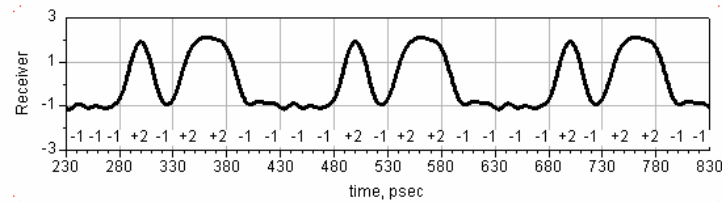


Fig. 7. Receiver filter response with sequence

To prove the ability of the transmitter and receiver filters to operate together as sequence encoder and detector, the circuits described above were tested in cascade, assuming perfect signal coupling between the two. Fig. 8 shows the outcome of such tests as resulting in near ideal 25 ps pulses repeating at 5 GHz. Such result shows that the impulsive autocorrelation function is in a good agreement with the theory of reciprocal sequences [Al-Dabbagh, *et.al.*, 1998] and clearly indicates the suitability of the proposed structures for use as very high rate communication encoders and decoders.

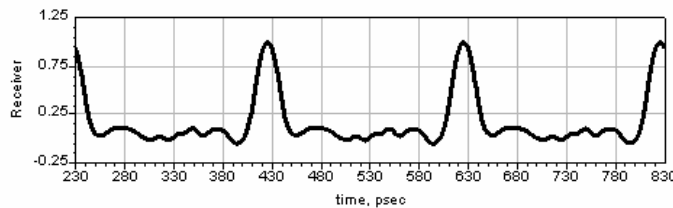


Fig. 8. MMIC transversal filter responses to a 5 GHz symbol rate

4 Contributions to Research Field

1. A novel distributed transversal filter topology, which is named the triple-line transversal filter, is developed for transmitter and receiver implementations. Due to its high frequency capabilities, the filter is appropriate for shaping / generation of multi-Gbit/s sequences.
2. A new approach for the design of distributed amplifier delay lines is proposed. A topology based on input line coupling capacitors was developed to achieve wideband impedance matching between filter cell sections and delay lines. The appropriate conditions for capacitor value choice were derived and such design was verified analytically.
3. A new tap gain weight control technique was specifically designed for the triple-line filter topology. The utilisation of such technique allows maintaining uniformity of the artificial transmission lines for continuous gain control.
4. A MMIC 7-tap transversal filter was designed using HEMT and microstrip technology for 40 Gbit/s systems applications. The MMIC transversal filter is based on the triple-line topology. Layout of the filter is presented and simulation results indicate the efficacy of the design techniques proposed in the thesis. The design proves to be stable at the design operation conditions.

5. An intuitive model of the distributed transversal filter that allows gaining an insight into the filtering of short pulses is established. The description of the model, which is in full agreement with simulation results, sustains that intrinsic limitations of the transversal filter make its optimisation in the time and frequency domain two different processes.
6. An incremental model of the filter cell was derived, from which the responses of the filter can be analysed by assuming differential-mode and common-mode wave propagation on artificial transmission lines. A set of differential scattering parameters were derived so as to analyse the responses of the filter. This work is based on the extension of the treatment given in [Bockelman and Eisenstadt, 1995] and specific to the distributed filter design.
7. Time domain simulations were carried out for theoretical and practical filter structures so as to analyse the effect of different components in the response. It is proved that the MMIC transversal filter design can maintain pulse shape integrity and low inter pulse interference.
8. The cascading of a transversal filter pair, acting as a transmitter and receiver, was analysed via reciprocal sequences. The output of the filter pair in cascade, which is effectively the convolution between two waveforms, maintains the in-phase amplitude of the convolution function. It is proved that the filter proposal satisfies the first Nyquist criterion.

5 Conclusions

The thesis reports novel circuit designs and design techniques that allow the generation and detection of different multi-Gbit/s CDMA signals using a simple, yet versatile, distributed amplifier structure. A novel structure was developed to effect transversal filtering functions that can be modified by changing the bias of the active devices employed. The main contributions of this thesis are in the design of the new circuits and in the development of systematic techniques to study the circuits' behaviour in the time and frequency domains.

Scattering parameters were used for frequency analysis. The MMIC transversal filter has the following characteristics: an input VSWR ratio of 1:1.5 with output reflection parameters practically independent of the tap gains and better than -18 dB. Both parameters are sustained over a substantial part of the operation bandwidth (close to 35 GHz). In addition, the low 3 dB cut-off frequency was equal to 23 MHz and is independent of tap gain settings. Those parameters indicate broadband behaviour regardless the coding. Stability analysis of the MMIC transversal filter was also carried out, showing appropriate stability parameters at the operating conditions.

Mixed-mode propagation analysis was developed for complete modelling of the designed three port distributed cell structure. Using such analysis, it was confirmed that the MMIC transversal filter has suitable transmission characteristics for reconfigurable filters. A set of time domain simulations were carried out on the distributed structure. Simulation results show that transmission line characteristics play a significant role in the transient response of the filter. It was proved that *inductor*-based transversal filter in general presents lower attenuation per section and higher transient components, which in turn increase inter pulse interference. The use of small damping resistors in delay lines improves the overall response as low transient components and more symmetrical pulses are obtained at the output. In spite of the above, the MMIC transversal filter was designed without dissipative components since microstrip transmission lines introduce a high level of loss and the transient responses were appropriate for the application. In such distributed filters, the tap gain compensation results in an efficient method for reducing the inter pulse interference that results from the combination of frequency-dependent attenuation and pulse dispersion. The ability of the transmitter and receiver filters to operate together as sequence encoder and detector was tested. Through the use of reciprocal sequences, the potential of such filters for the reception / generation of waveforms featuring pre-specified correlation properties were demonstrated. The cascade of such distributed transversal filter should allow an increase on the length of CDMA processors. By testing with different sequences and showing its effective generation and reception, without compromising the performance, it is shown that the proposed filter is versatile and the developed methods are appropriate. The resulting structure can be used in a variety of applications where pulse shaping and filtering is needed at rates up to several tens of Gbit/s.

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Izzat Darwazeh. He obtained his first degree in Electrical Engineering from the University of Jordan in 1984. He obtained the MSc and PhD degrees, from the University of Manchester Institute of Science and Technology (UMIST), in 1986 and 1990, respectively. He worked as a research Fellow at the University of Wales - Bangor -UK from 1990 till 1993, researching very high speed optical systems and advanced MMICs for optical communications applications. He was a Senior Lecturer in Optoelectronic Circuits and Systems in the Department at Electrical Engineering and Electronics at UMIST. He moved to University College London in October 2001.