High-Speed Generalized Distributed-Amplifier-Based Transversal-Filter Topology for Optical Communication Systems

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***Abstract*—The use of a distributed-amplifier-based transversal filter as a signal processor for high-rate pulse shaping/filtering is discussed. By showing the analogy between transversal filters and distributed-amplifier topologies, schemes demonstrating practical approaches for the design of such filters are explored. The practicability of one of the different schemes is illustrated via an implemented design. A four-stage 40-Gb/s distributed-amplifier monolithic microwave integrated circuit (MMIC) is constructed using one of the developed schemes and its behavior is discussed.**

***Index Terms*—Distributed amplifiers, filters, MMIC amplifiers, optical receivers, transversal filters.**

I. Introduction

Traditionally, optical-fiber receiver design requires a front-end preamplifier to be followed by a pulse shaping filter to improve the overall performance and minimize the error rate. Such an implementation adds complexity to the design of the receiver. An alternative method is to tailor the preamplifier response so that it matches the response of the required filtering transfer function. In this method, the pulse shaping/filtering is embedded in the preamplifier itself, which is desirable since it minimizes the number of system components, which consequently reduces the number of circuit interconnections. This can be translated into a reduction of production and packaging costs and improved circuit and system reliability [2].

High-speed optical communication systems require wide-band amplifiers capable of handling pulses with widths in the region of tens of picoseconds. Optimum performance of such systems is obtained if these pulses satisfy specific time/frequency-domain characteristics. Inherently, distributed amplifiers can operate up to frequencies close to f_T of their active devices [3] and, therefore, offer a very attractive option for such systems. Jutzi was the first to demonstrate the use of distributed amplifier as an active transversal filter for low microwave frequencies [4]. Recently, using a novel technique, a distributed amplifier was conceptually demonstrated to behave as an active pulse shaping/filtering network [5] by effectively constructing it as a transversal filter. This was achieved by setting different stage gains while equalizing the differential delays of all amplifier stages by means of additional delay lines in the gate artificial transmission line, so that a desired target response was obtained.

In this paper, an extension of the work in [5] and detailed treatment of the work in [6] are presented. Two topologies demonstrating practical approaches to the design of the distributed-amplifier-based transversal filters are considered. The designs techniques developed are illustrated by means of a practical post-detection filter example aimed at designing a 40-Gb/s amplifier with embedded 100% raised cosine (RC) shape using a 40-GHz high electron-mobility transistor (HEMT) coplanar-waveguide monolithic-microwave integrated-circuit (MMIC) process. The predicted performance is detailed and compared to the prespecified target performance.

The structure of this paper is as follows. Section II describes the analysis of the distributed-based transversal-filter topologies. Section II lists the possible circuit configurations based on the distinguished topologies. Section IV lays out the design procedure of these amplifiers with embedded signal shaping. Finally, based on the treatment illustrated in this paper, Section V is devoted to the performance of a fabricated chip using a 40-GHz MMIC process.

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II. Distributed Transversal-Filter Structure: Analysis

Conventional distributed amplifiers developed for microwave and millimeter-wave applications have symmetrical input and output artificial lines constructed by a series of distributed transmission lines and the parasitic capacitances of their active devices [7]. Therefore, the cutoff frequencies of the artificial lines are very high and consequently these amplifiers have inherent broad-band characteristics without the effect of the parasitic capacitances [3]. A circuit diagram of such amplifiers is shown in Fig. 1. In this paper, the interest lies in amplifiers with embedded signal shaping and, therefore, we present the analogy between generalized distributed amplifiers

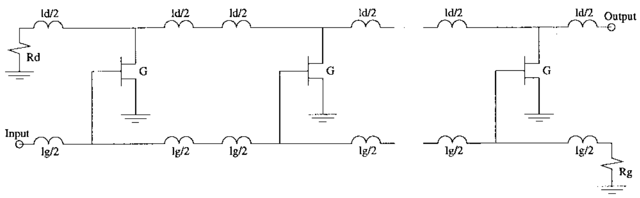

Fig. 1. A conventional distributed-amplifier circuit diagram.

and transversal filters. Two topologies are distinguished—each with four possible schemes.

A generalized transversal structure normally used for low-frequency signal processing applications, is illustrated in Fig. 2. The filter consists of a delay line with maximum delay $\sum_{i=1}^{N} \tau_i$ and $N+1$ taps, where N is the number of delay-line sections and τ_i is the delay of the ith section. A signal travelling along the delay lines is sampled at each tap output. The sampled outputs are multiplied by the gain coefficients $G_1, G_2, \cdots, G_{N+1}$ and summed to form the final output. Hence, the time-domain output response of such a structure is given by

$$x_{\mathrm{out\,TF}}(t) = \sum_{k=1}^{N+1} G_k x_{\mathrm{in}}\left(t - \sum_{i=0}^{k-1} \tau_i\right) \qquad (1)$$

where $\tau_o = 0$ and the subscript TF signifies transversal filter. The frequency-domain transfer function can be obtained by applying Fourier transform to (1) giving

$$H_{\mathrm{TF}}(\omega) = \sum_{k=1}^{N+1} G_k \exp\left(-j\omega \sum_{i=0}^{k-1} \tau_i\right). \qquad (2)$$

Possible implementations of the structure shown in Fig. 2 for microwave-frequencies operation is rather complicated and difficult to produce in integrated form. Two alternative generalized transversal filters based on a distributed structure are illustrated in the block diagrams shown in Fig. 3. In this figure, G_k is the gain of stage k and τ_{g_k} and τ_{dk} are the respective interstage delays of the gate and drain artificial transmission lines. The signal at the output of the general distributed amplifier based on the first topology shown in Fig. 3(a) in the time domain is given by

$$x_{\mathrm{out\,DA}}(t) = \sum_{k=1}^{N+1} G_k x_{\mathrm{in}}\left(t - \sum_{i=0}^{k-1} \tau_{g_i} - \sum_{j=k}^{N} \tau_{dj}\right) \qquad (3)$$

where $\tau_{g_o} = 0$ and DA signifies distributed amplifier. Its transfer function is given by

$$H_{\mathrm{DA}}(\omega) = \sum_{k=1}^{N+1} G_k \exp\left(-j\omega\left(\sum_{i=0}^{k-1} \tau_{g_i} + \sum_{j=k}^{N} \tau_{dj}\right)\right). \qquad (4)$$

By equating (2) and (4), we get

$$\sum_{i=0}^{k-1} \tau_i = \sum_{i=0}^{k-1} \tau_{g_i} + \sum_{j=k}^{N} \tau_{dj}. \qquad (5)$$

By expanding (5) for values of k from 1 to $N+1$, we get $(N+1)$ equations in τ's whose solutions are given by

$$\tau_k = \tau_{g_k} - \tau_{dk}. \qquad (6)$$

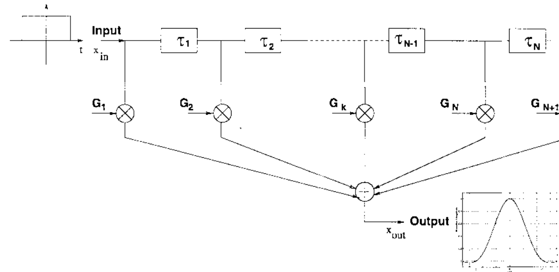

Fig. 2. A generalized transversal-filter block diagram.

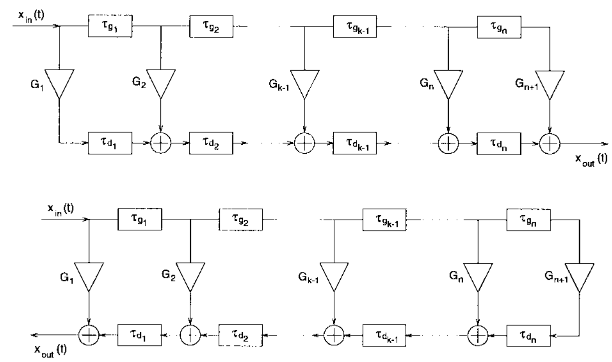

Fig. 3. Two distributed-based transversal-filter topologies.

The signal at the output of the general distributed amplifier based on the second topology [shown in Fig. 3(b)] in the time domain is given by

$$x_{\mathrm{out\,DA}}(t) = \sum_{k=1}^{N+1} G_k x_{\mathrm{in}}\left(t - \sum_{i=0}^{k-1} (\tau_{g_i} + \tau_{di})\right) \qquad (7)$$

where $\tau_{g_o} = \tau_{do} = 0$. Its transfer function is given by

$$H_{\mathrm{DA}}(\omega) = \sum_{k=1}^{N+1} G_k \exp\left(-j\omega \sum_{i=0}^{k-1} (\tau_{g_i} + \tau_{di})\right). \qquad (8)$$

By equating (2) and (8) we get

$$\sum_{i=0}^{k-1} \tau_i = \sum_{i=0}^{k-1} (\tau_{g_i} + \tau_{di}) \qquad (9)$$

which yields

$$\tau_k = \tau_{g_k} + \tau_{dk}. \qquad (10)$$

Therefore, the stage delay of the transversal filter is functionally equivalent to the stage differential delay of the distributed amplifier based on the topology shown in Fig. 3(a) and to the stage additive delay of the distributed amplifier based on the topology shown in Fig. 3(b). For MMIC implementation, the gain coefficients are determined by the transconductances of the common-source FET's and the equivalent tap delay lines are essentially determined by the delays of the gate and drain transmission lines [5]. The transconductances are set by controlling both the effective FET areas and the bias current. A transversal filter based on distributed structure suitable for MMIC implementation is illustrated in Fig. 4. The rectangular boxes shown in this figure represent inductors implemented as short-length transmission lines.

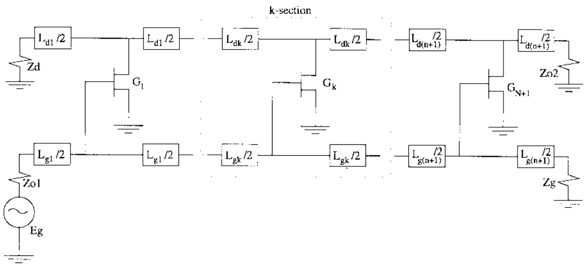

Fig. 4. A distributed-amplifier circuit diagram.

III. Circuit Configurations

Distributed amplifiers are traditionally used for providing a flat gain response. In such a case, all the active devices are of the same size and a capacitance parallel with the drain-to-source capacitance $C_{\rm gs}$, or alternatively, a transmission line in series with the drain line is used to equalize the drain and gate artificial line delays (zero differential delay between the drain and the gate lines). When signal shaping is required (where the differential delay is not zero) this constraint is removed, allowing a simplified distributed-amplifier implementation.

Since two main variables control the performance of the transversal filter based on Fig. 2, namely, gains G_k and delays τ_k, four distributed-amplifier implementations of transversal filters can be identified. These are:

- case 1: equal τ_k and unequal G_k;
- case 2: equal τ_k and equal G_k;
- case 3: unequal τ_k and equal G_k;
- case 4: unequal τ_k and unequal G_k.

Case 1 corresponds to the conventional transversal filter. This case was dealt with in detail in [5] by Moreira *et al.* in the context of optical receiver preamplifiers with embedded signal shaping where the number of gain elements, representing the stage amplifiers and the gain values, were determined from a target time-domain response by uniform sampling. Due to the symmetry of the impulse response, this number was chosen to be odd. Although good results were reported using this approach, the wide transmission lines required to extend the interstage delays may result in implementation difficulties. Case 2 is the case of a simple low-pass filter where the stage delays are equal and the stage gains are equal. Here, a very high frequency low-pass filter with gain can be implemented. The cutoff frequency of such a filter is governed by the cutoff frequency of the gate and drain transmission lines. Although this approach is simple, it has few degrees of freedom to control the out-of-band frequency response. Case 3 is the case of the transversal filter where all stage gains are equal and stage delays are different. Case 4 is the most general case where both the gains and the stage delays are different. Case 4 allows maximum flexibility and has the highest number of degrees of freedom among all the cases. The results of one approach (case 3) for the topology of Fig. 3(a) will be discussed in this paper.

IV. Design Procedure

In this section, a step-by-step method is described for designing distributed amplifiers based on cases 3 and 4. In Fig. 2, we add the input/output signal shapes. The signal shapes considered here are assumed to be a square nonreturn to zero (NRZ) input and a 100% RC output. The method is not restricted to a particular input/output shape and could be applied to a variety of signals suitable for optical or wide-band microwave systems. The main steps to be followed when designing distributed amplifiers based on case 3 are outlined below.

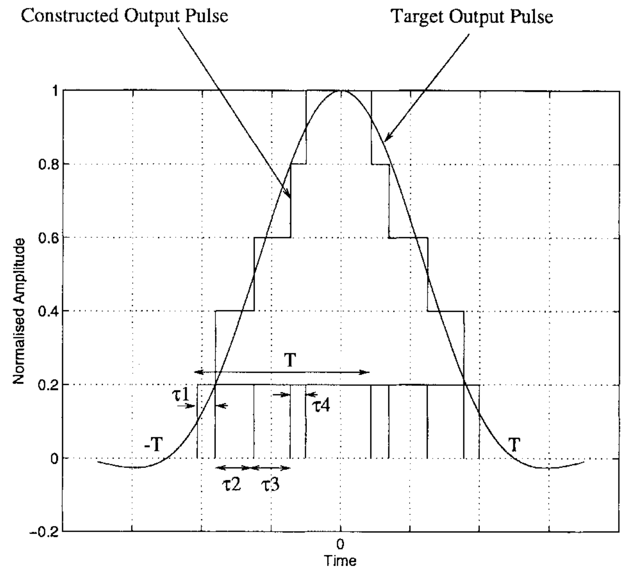

Fig. 5. Delay determination for a five-stage DA based on case 3.

1) Since the gains are equal, only the delays should be calculated. This is done graphically by superimposing a pulse with duration T then shifting it to the right in such a way that more shifts are made where the curvature of the output pulse is not linear, as illustrated in Fig. 5. Although the obtained values of the delays τ_k will not be exact for the final distributed-amplifier design, they serve as a good estimate for starting values in the design process.
2) The values of inductors of the drain and the gate transmission lines are calculated using values of τ_k from step 1, (6) for DA topologies based on Fig. 3(a) or (10) for those based on Fig. 3(b) and using the fact that the delay of an L-section network consisting of an inductor L and a capacitance C is equal to $\sqrt{LC}$. Equivalent transmission-line lengths are obtained to replace the inductors, for high-frequency designs.
3) Circuit simulation and layout tuning is then carried out to correct for nonidealities (losses, device parasitics, and the degeneracies of the MMIC process used).

The same steps are followed when designing distributed amplifiers based on case 4 except in (1) the pulses are multiplied by appropriate factors and then shifted to fit the output pulse. Here, the factors G_k are related to the transconductances of the FET's by the following relation:

$$\frac{g_{mk}}{\max(g_{mk})} = \frac{G_k}{\max(G_k)}. \tag{11}$$

Note that for this case, if FET's are to be biased, separately blocking capacitors have to be inserted in the gate of each

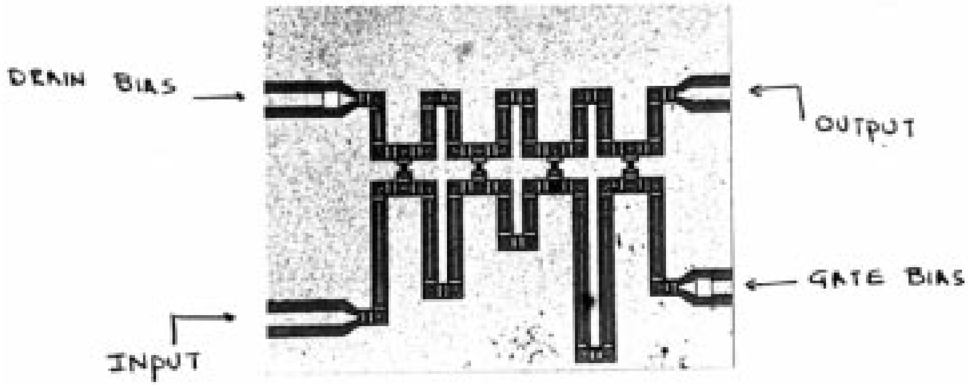

Fig. 6. Photomicrograph of the fabricated chip-dimension $2 \times 1.5\ \mu m^2$.

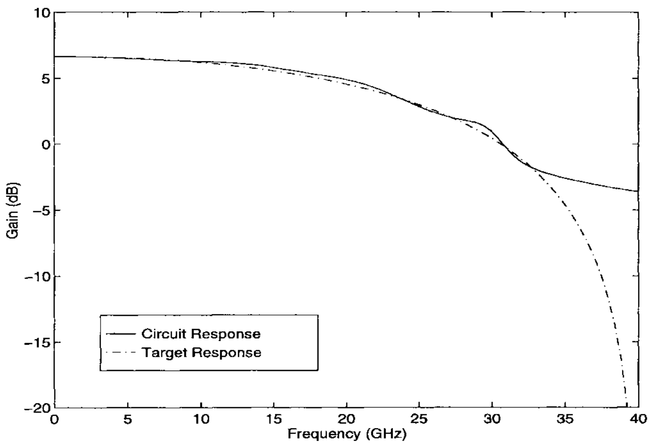

Fig. 7. Circuit response (solid line) and target response (dashed–dot line) for the fabricated DA.

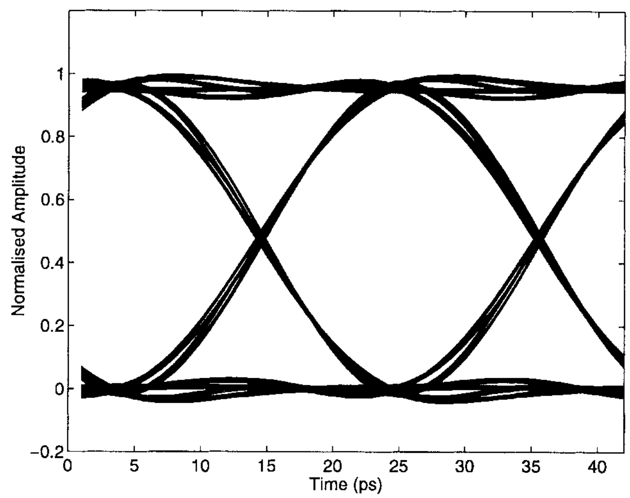

Fig. 8. Eye diagram for the fabricated four-stage DA based on case 3.

FET of Fig. 4, otherwise FET's of different sizes should be used [8].

V. Results

Based on the topology shown in Fig. 3(a), the new schemes (cases 3 and 4) have recently been applied [6] to the design of a five-stage 40-Gb/s distributed amplifiers with an RC-output function for an ideal rectangular pulse input. In this section, we will make use of the analysis presented above to design a practical distributed-based transversal filter based on the topology shown in Fig. 3(a). It should be noted that in the design of distributed-based transversal filters where the interstage delays result into very long impractical transmission lines, the second topology is favored as the total delay will be the addition of the gate and drain stage delays [see (10)]. A 10-GHz DA design based on this topology has recently been reported by the authors [8] and, hence, will not be addressed in this paper.

Based on case 3 for the first topology [see Fig. 3(a)] and using a 40-GHz HEMT–MMIC process, we design a four-stage distributed-based transversal filter. In this process, transmission lines are implemented in coplanar waveguide technology. Coplanar waveguides offer two main advantages over miscrostrip lines in the design of distributed amplifiers: source grounding of the active devices is done easily without the use of via holes (as in the case of microstrip [5]), and if a relatively wide ground plane exists between two adjacent transmission lines, coupling problems are reduced resulting in potentially more compact designs. In this case, once the size of the active devices is selected, only the lengths of the gate and drain transmission lines are calculated as mentioned above in the design procedure. Four 2 μm $\times$ 25 μm 0.3-μm enhancement HEMT's are used. The photomicrograph of this DA is shown in Fig. 6 and its size is 2 μm $\times$ 1.5 μm. Notice that the transmission lines are meandered to make the chip more compact. The four-stage distributed amplifier based on case 3 was built and optimized, using the smart libraries available for the MMIC process, taking into account the effect of bends, double bends, and air bridges. The optimum circuit response of this distributed amplifier was achieved by comparing the s_{21} response to the target response and is shown in Fig. 7 contrasted to the target response. The target response is a function of the output signal shape. For the design discussed, the required output signal is a 100% RC and optimization was carried out to a frequency of 35 GHz. The RC target has a zero at 40 GHz which is not possible to realize using a pole-only distributed-amplifier circuit; hence, the discrepancy between the target and circuit responses at frequencies above 35 GHz. The simulated eye diagram obtained for this MMIC from frequency-domain data for $2^7 - 1$ pseudo-random binary sequence (PRBS) NRZ input data is shown in Fig. 8. The RC shape and the low inter symbol interference (ISI), evident in the figure, clearly illustrate that s_{21} discrepancy between the target and circuit responses at frequencies beyond 35 GHz have little effect on the time-domain behavior of the amplifier, indicating the efficacy of the signal shaping using the third scheme.

VI. Conclusion

The analogy between the distributed amplifier and the transversal filter has been further developed. Based on two different topologies, two possible schemes representing a practical approach to the construction of such amplifiers have been explored. Based on one of the developed schemes and using a 40-GHz HEMT–MMIC process, a chip was produced with results reported showing the efficacy of the new schemes for signal shaping and filtering at microwave frequencies.

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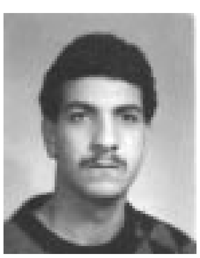

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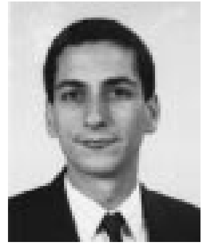

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