Communications Research Centre

A STUDY OF REFLEX OPTOELECTRONIC SWITCHING MATRICES AND THEIR DERIVATIVES

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ABSTRACT

The application of Reflex Optoelectronic Switching Matrices (ROSM) to signal processing in the GHz region is analyzed. Various signal processing functions such as delay generation, loop filtering, word generation-/detection, integration and digital to analog conversions are identified and their respective realizations in a ROSM are presented. It is found that for dedicated signal processing functions, simpler sub-matrices instead of full matrices can be employed with significant reduction in complexity and cost. The performance of ROSMs using currently commercially available components confirms the feasibility of GHz signal processing with ROSMs.

1. INTRODUCTION

Reflex Optoelectronic Switching Matrices (ROSMs) are arrays of detectors acting as addressable crosspoint elements in conjunction with a set of appropriately chosen delay lines operating as feedback paths. The large bandwidth, high isolation and fast switching in ROSMs offer the capability of routing broadband signals through networks. The feedback paths allow various signal processing to be done through real time circulation and sampling of analog or digital waveforms analogous to transversal filtering operation. The preliminary proposal and evaluation of ROSMs has been reported earlier [1,2]. The purpose of this technical note is to analyze in detail their full capabilities and performance.

An 8x8 ROSM is shown schematically in Fig. 1. The input signals are converted to optical carriers by means of laser diodes or LED's. The light is distributed to the crosspoint elements by optical waveguides and optical waveguide power dividers. The excellent isolation between optical waveguide signal paths is the basis for the immunity of the array to crosstalk between ports. The crosspoint switches are optical detectors that can be rendered sensitive or insensitive to optical signals. Photoconductive detectors, pin and APD devices can be used for this purpose, with the switching function provided by bias control. The electrical signals from

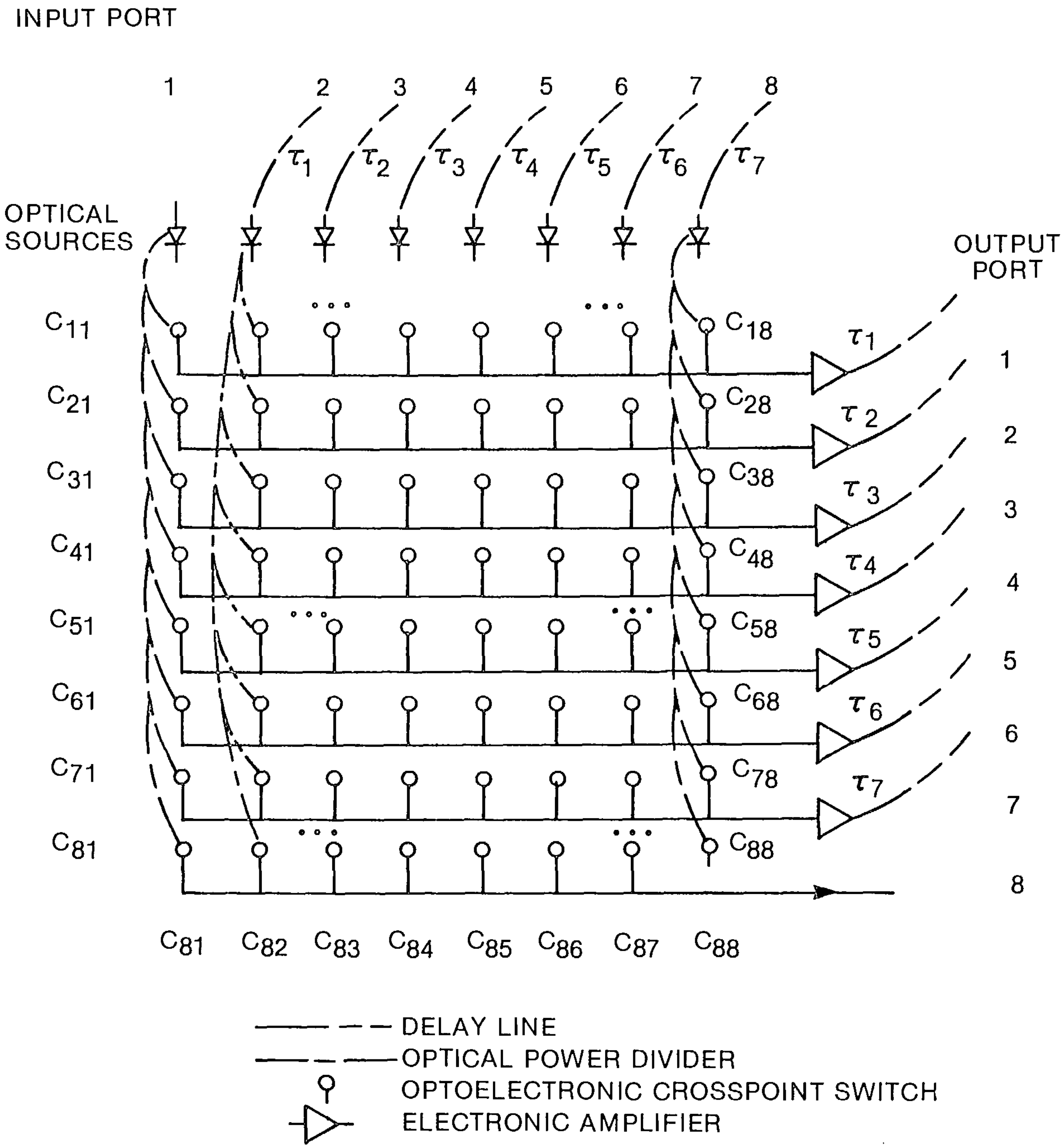

Figure 1. An 8x8 Reflex Optoelectronic Switching Matrix (ROSM).

the detectors are summed into the output ports. Thus any input (electrical) signal can be made to appear at any output port by choosing appropriately the biasses on the crosspoint photodetectors. With photoconductive detectors this summation can be obtained merely by a common connection for one of the terminals of the photoconductor group connected to a particular output port, and can be achieved as an integrated part of a monolithic array of photoconductors [3]. Since the physical spacing of the photoconductors is very much less than a signal wavelength, the actual layout of the common connection is not critical, and the summation function is easily achieved. Output ports 1-7 have delay lines feeding back signals to the input ports 2-8. The result is that any combination of generation or circulation of signal is possible by addressing the appropriate crosspoint elements. Input port 1 represents the connection for incoming signal or trigger pulse. Activating the crosspoint elements along output port 8 causes real time sampling of the signals as the latter are being circulated in the ROSM.

The matrix constructed as shown in Fig. 1 is a full matrix which provides all the possible signal processing functions and the maximum versatility. It is however not necessarily the ideal set up for situations where only specific and dedicated functions are desired. The simplification is done by first identifying submatrices in the full matrix which perform specific functions. Referring to Fig. 1, it can be seen that vectors $C_{1,j}(j=1,8)$ and $C_{i,8}(i=1,8)$ are the fundamental input and output ports respectively. The diagonal vector $C_{i,j+1}(i,j=1,7)$ serves as the looping crosspoint for any single or combination of delay lines. Crosspoints in the lower triangle - beneath the diagonal vector - $C_{i,j}(i=2,7,\ j=2,i)$ or the upper triangle - above the diagonal vector - $C_{i,j}(i=1,6,\ j=i+2,8)$ provide the connections for serial addition of delay lines. One group is therefore redundant for serial addition purposes. Only in the case of parallel or serial looping of combination of delay do both groups together with the diagonal vector (which means a full matrix) becomes necessary. However, even in this case, there may not be a need for a full matrix if the desired functions do not form a complete set. For instance, in word pattern recognition where there is only a limited variation of word pattern, it is possible to tailor the ROSMs to recognize only this limited variation of word pattern. The result is a reduction of components which means simplicity and cost efficiency. In addition to this, improvement in the speed of response is possible as will be shown later.

2. SIGNAL PROCESSING OPERATION

The signal processing functions that will be discussed here are as follows: (i) Delay generation, (ii) loop filtering, (iii) word generation, (iv) word detection by correlation, (v) integration/digital to analog conversion. Each function will be presented in respect of the submatrix that can accomodate a complete set of connections. Further simplification of the submatrix is therefore possible for situations where only a limited set is encountered. Simpler derivatives of the submatrix where applicable are also presented.

2.1 DELAY GENERATION

The generation of delay is done by biassing a number of crosspoint elements in the ROSM so that the signal at Input port 1 circulates through one or a number of delay lines prior to being sampled out at Output port 8. For instance, biassing C_{11}, C_{22}, C_{83} causes a delay generation of $\tau_1 + \tau_2$. For an 8x8 matrix (i.e. N = 8) with N-1 = 7 delay lines, if the delay lines are related to each other through power of 2, with a minimum delay of τ, then a total of 2^{N-1} = 128 delays from 0 to 128τ, in increments of τ, can be generated. The reduction of the full matrix to a submatrix arises from redundancy between the lower and upper triangular elements as discussed earlier. Fig. 2 is a representation of the submatrix. For N = 8, the saving of crosspoint elements in the submatrix is N(N-1)/2 = 28 out of a full matrix of NxN = 64. The number of amplifiers or total gain required to offset the insertion loss is therefore less because the optical power division is less on the average. This can also mean that less expensive lasers and detectors can be employed. Also, the addressing of crosspoint elements can be achieved at higher speed due to the reduction in size.

2.2 LOOP FILTERING

Loop filtering is done by recirculation of signals through a single, or a serial or parallel combination of delay lines. This is where a full matrix is necessary in order to allow any combination of loopings. The required configuration is therefore identical to Fig. 1. Serial looping of a combination of delay lines is done by utilizing both the lower and upper triangular elements. For instance, recirculation through loop $\tau_2 + \tau_4$ requires the biassing of C_{21}, C_{43}, C_{25} and C_{85}. Parallel looping is done by activating the individual loops and summing them at the crosspoint elements along Output port 8. Significant reduction of components occurs when only looping of single delay line is required. The desired submatrix in this case is shown in Fig. 3 which only consist of the input, output and diagonal vectors. The latter provides the looping point for single delay. Optical power division of 2 only is required in this case.

2.3 WORD GENERATION

The submatrix for word generation is shown in Fig. 4a. Its operation is carried out by introducing an initial pulse at the Input port 1 and addressing all the crosspoint elements along Input port 1 so that the signal is reproduced 8 times. The 8 identical signals propagate through the set of delay lines which are linearly (instead of power of 2) related. That is $\tau_7 = 7\tau_0$, $\tau_6 = 6\tau_0$ ... $\tau_2 = 2\tau_0$, $\tau_1 = \tau_0$. The initial pulse can be eliminated or kept as a synchronization trigger by withholding or applying bias to crosspoint element C_{81} respectively. The sampling of the eight circulating signals to form a digital work is done by addressing the crosspoint elements along Output port 1. For example, a bit pattern of 11100110 is generated by activating $C_{11} \rightarrow C_{81}$, C_{82}, C_{83}, C_{86} and C_{87}. A derivative of this approach is to eliminate the recirculating function and apply switching bias to the laser instead of the detector. This is however not very effective because

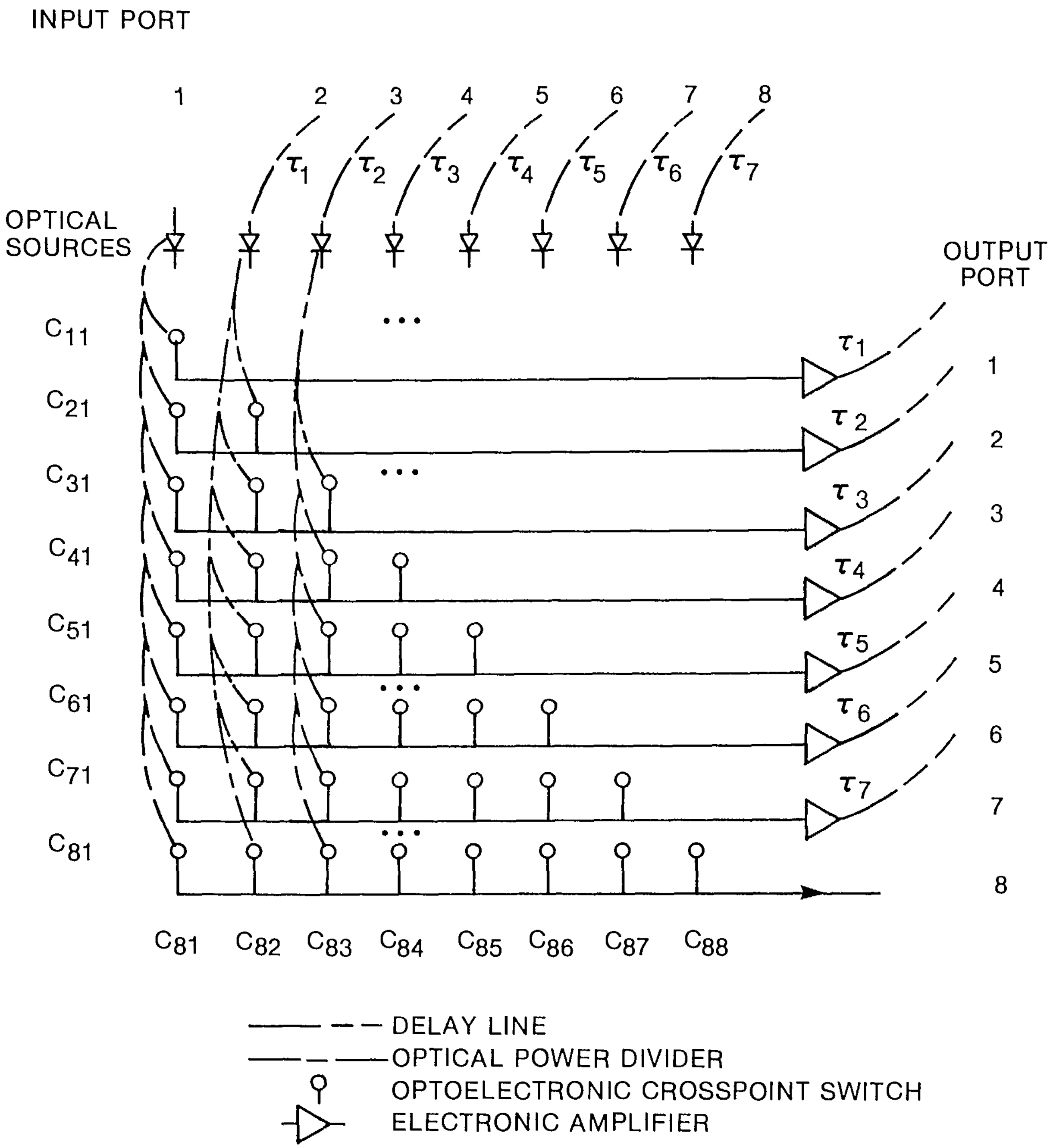

Figure 2. A Submatrix for Delay Generation.

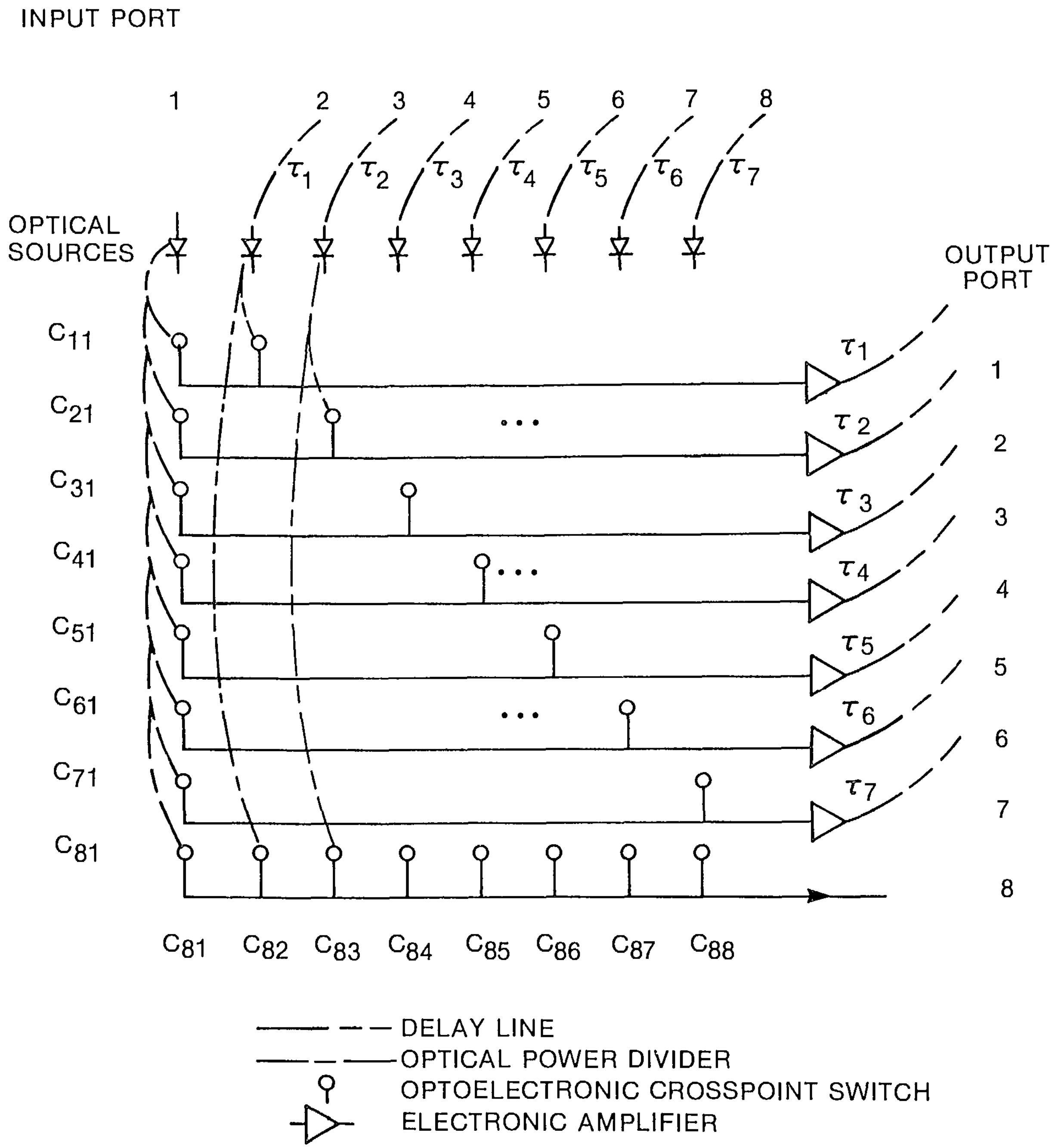

Figure 3. A Submatrix for Loop Filtering which Involves Single Delay Line Only.

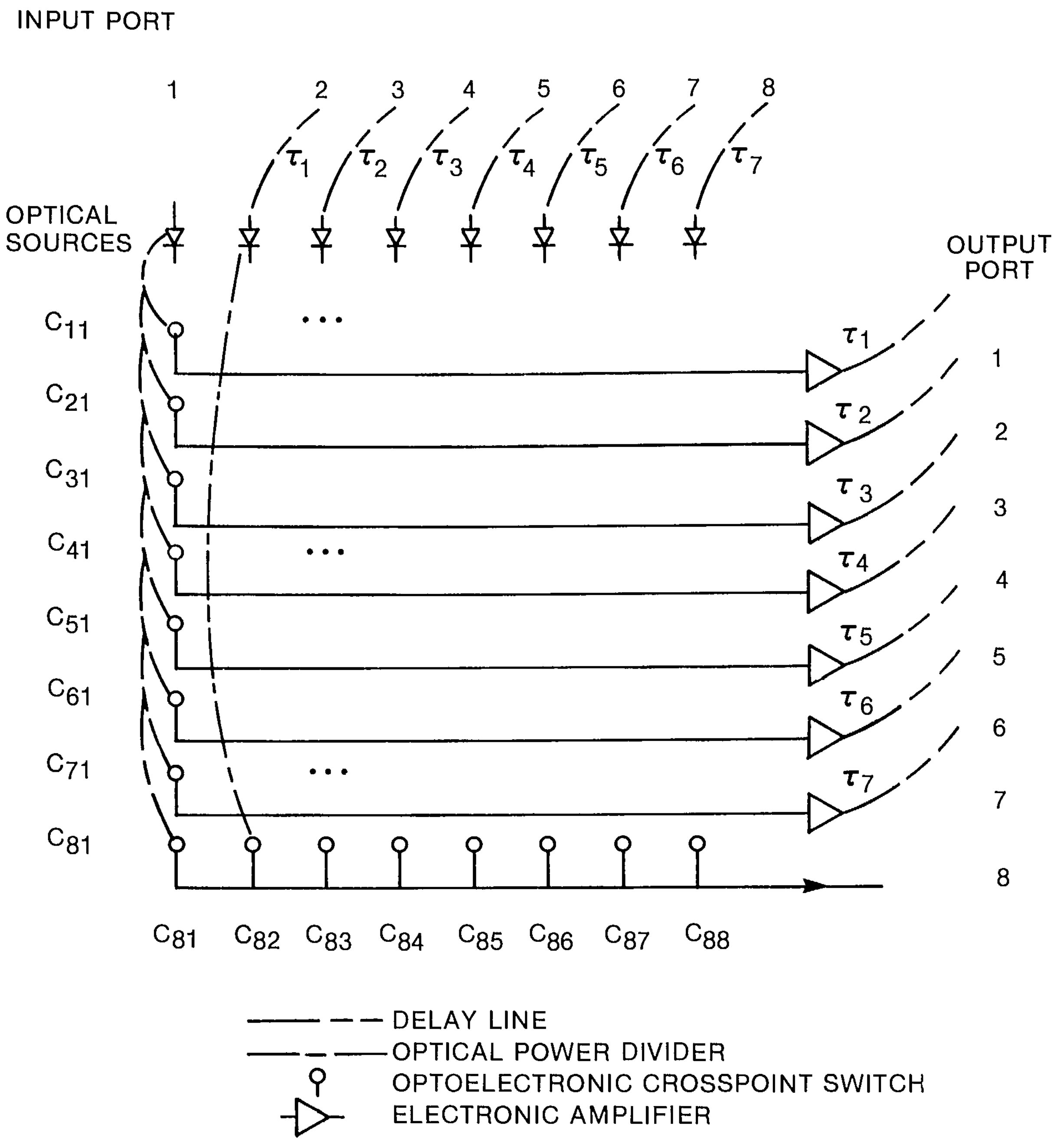

Figure 4a. A Submatrix for Word Generation.

of transient effect or spurious signal despite zero bias. Alternatively, the signal driving the laser can be gated as shown in Fig. 4b. The advantage of generating word pattern using many lasers instead of one laser alone is that it bypasses the laser resonance problem at high frequency. The bit rate here can be limited by only the shortest attainable pulse from the lasers which can be very small.

2.4 WORD DETECTION BY CORRELATION

The basic submatrix is similar to that of word generation shown in Fig. 4a. The operation is however different in that the reverse order of the incoming bit pattern is applied to the crosspoint elements in order to achieve correlation. A reverse version of Fig. 4b is shown in Fig. 5 and it represents a simple derivative to perform correlation. Here the recirculating function is eliminated and the reverse order of the bit pattern is applied to the detector array.

2.5 INTEGRATION/DIGITAL TO ANALOG CONVERSION

So far, the bias condition has always been quasi-DC in that it is in steady state during the generation or detection of a delay or a word. If the bias condition is varied according to the incoming bit rate, then other functions can be obtained. Referring to the circuit in Fig. 5, if the bias is applied to the detector with the largest delay and then sequentially shifted to the next detector at the incoming bit rate, the resultant output is integration of the detected word. The shifting function can be easily done by shift registers or counters. If further to this shifting bias, weighting functions are applied to the detector outputs by adjusting their bias or adding variable attenuators following them such that the value of each bit is differentiated, digital to analog conversion is achieved. The weighting can be obtained too by simply adjusting the coupling ratio of the various optical fibre output arms.

3. PERFORMANCE

The performance of the ROSM in terms of its bandwidth and minimum delay is related to a number of factors: the external electronics that drive the laser and address the crosspoints, the laser, detector, amplifiers, and the optical power divider. The efficiencies of the lasers, detectors and power dividers determine the insertion loss and hence the required gain of the amplifiers to achieve zero loop loss. They therefore indirectly affect the minimum delay performance.

Some of the very best comercially available laser diodes exhibit an efficiency of 0.4 W/A. This together with pin diodes or photoconductors of responsivity 0.6 A/W give a minimum loss factor of 0.24 or 6 dB power. Coupling loss at laser and detector end further increases this to 8 dB. An 1x8 fibre coupler (made in-house) has an insertion loss of 3 dB and a dividing loss of 9 dB. Electrical mismatch and reflection can cause an additional 2 dB loss. The total loss is then 22 dB power or 44 dB

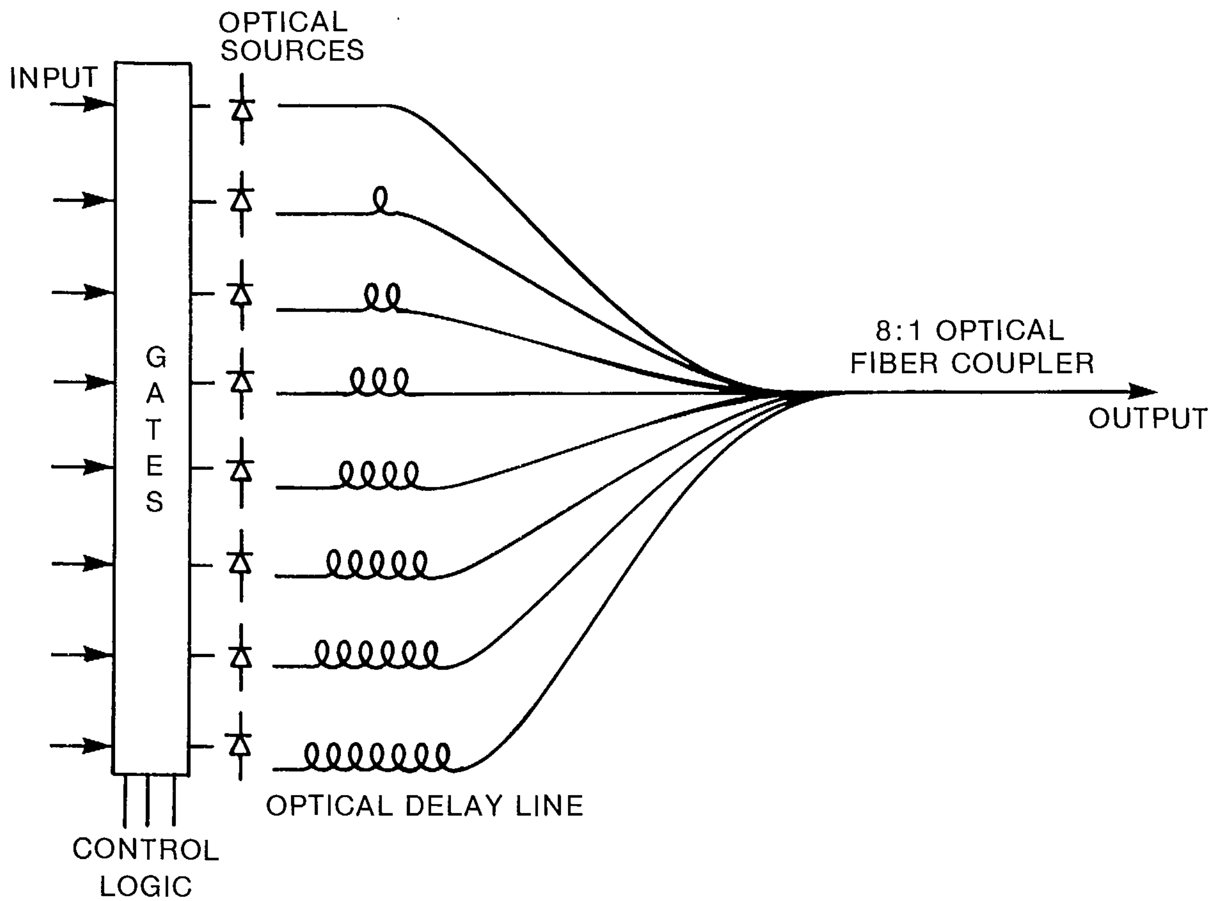

Figure 4b. A Derivative Approach for Word Generation.

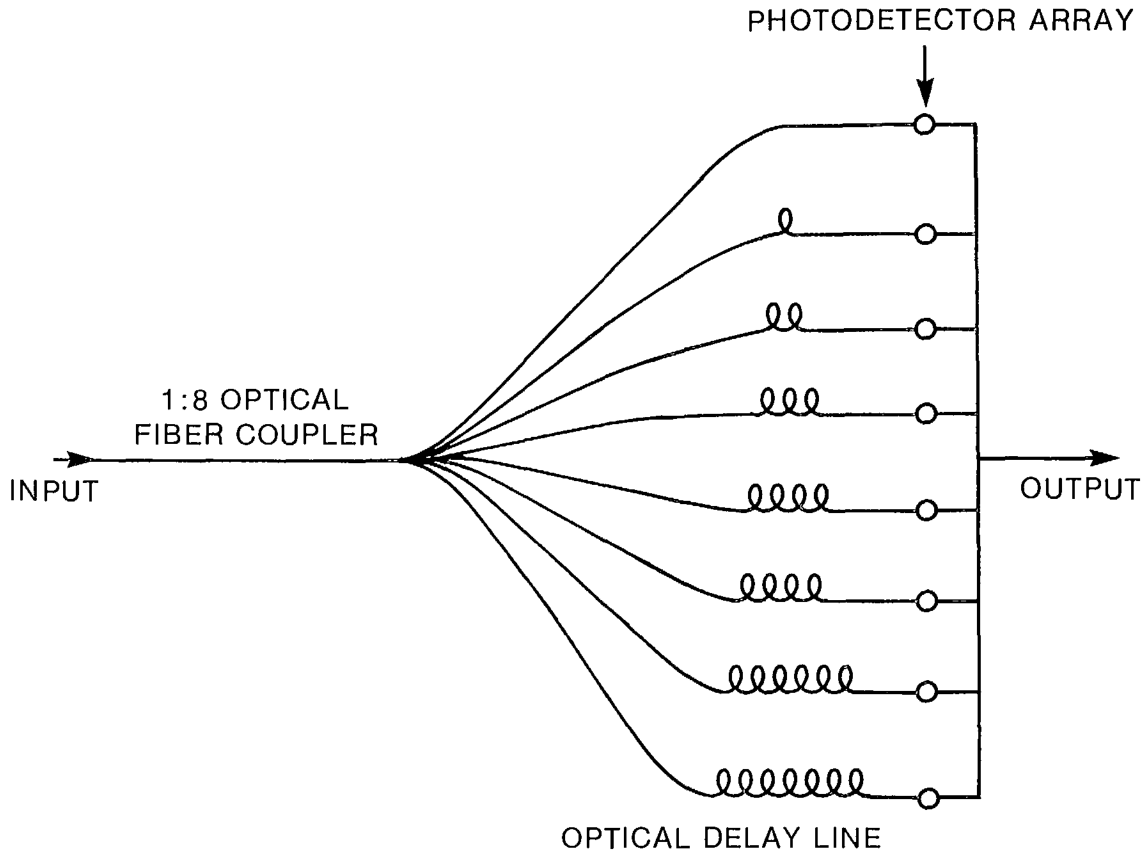

Figure 5. A Submatrix for Word Detection, Integration and Digital to Analog Conversion.

electrical. There are commercially available amplifiers having ≈ 20 dB gain, 7 GHz bandwidth and 0.6 ns propagation delay. The propagation loss in the delay line is negligible and hence two such amplifiers will be able to offset the total insertion loss. The laser turn-on delay can be eliminated by suitably biassing the lasers to just below threshold. For fast electrical switching speed, the GaAs photoconductor is one of the proper choices. It offers 0.6 ns switch-on time at a few volt bias [4]. Semiconductor laser pulses as short as 23 ps have been reported [5]. The external electronic circuits for driving the laser can have very fast response time whereas that for addressing the crosspoint detectors is limited to 3-4 ns for an 8x8 full matrix. Using optical fibre as delay line which has propagation characteristics of 1 dB/km and 20 cm/ns, negligible loss and very fine resolution are attainable.

According to the information above, an 8x8 full matrix will therefore have a minimum delay around any loop - excluding that from the intentional delay line - equal to the sum of detector switching speed and its associated electronic circuit, laser driver circuit and two amplifiers propagation delay. By applying the output of the amplifier directly to the lasers through properly matched microstripline circuit, the laser driver delay becomes insignificant. The minimum delay becomes [0.6 (detector switching) + 3 (detector addressing circuit) + 1.2 (2 amplifiers)]ns = 4.8 ns. The major factor here is the electronic addressing circuit. If submatrices are used for the respective desired function, the addressing time is decreased due to the reduced size of the matrices. And if the matrix is operated in a quasi-DC mode which means all the addressing is done in steady state and prior to the impulses driving the lasers or the arrival of the incoming signals, the minimum delay then becomes a function of only the amplifiers. In this case, any improvement in the loop loss directly results in less required gain and hence smaller minimum delay. The advantage of using submatrices becomes obvious as the optical power divider loss is much less. The minimum delay in an 8x8 full matrix operating under quasi DC conditions is therefore the amplifier delay of 1.2 ns. This is an important number as it determines some of the fundamental limitations of the full matrix. For instance, it represents a quantization error introduced in serial addition of delay line. In essence then, it sets an effective resolution limit of delay generation. The maximum frequency separation between consecutive passbands in loop filters is equivalent to its reciprocal (0.83 GHz).

The bandwidth of the matrix depends on what function is being implemented. There are 2 different cases to be distinguished. In the first case, the laser will be triggered only once during each complete cycle of delay or signal processing of a word of length N. The relevant functions are delay generation, word generation/detection, integration and digital to analog conversion. In the second case, the laser will be triggered at a much higher rate as in the case of loop filter. The bandwidth limitation in the first case is the minimum of that of detector, laser x N and laser driver circuit x N. The multiplication factor N follows accordingly from one trigger per cycle. The laser resonant effect at high frequency is therefore bypassed by using a matrix. The bandwidth is usually limited by that of the detector which is ≈ 3.75 GHz in the case of GaAs photoconductors studied here. The bandwidth for loop filter operation is limited by the laser which is ≈ 1 GHz for ordinary lasers. There have however been recent reports on direct modulation of lasers up to 7-10 GHz [6,7].

From the data and discussion provided above, the characteristics of various signal processing functions can be estimated. Quasi-DC operation is assumed for all functions except integration and digital to analog conversion which requires sequential strobing of the detector with respect to the incoming bit rate. Broadband amplifiers, and negligible laser driver circuit effects are also assumed. The delay generator shown in Fig. 2 has a detector limited bandwidth of 3.75 GHz and a minimum delay of 1.2 ns. Loop filter operation is limited by laser resonance at 1 GHz. Word generation using Fig. 4a is again limited by the detector. For Fig. 4b, the bit rate is limited by the detector whereas the word repetition rate is limited by the external gating circuit. Current fastest gates have 2 GHz BW. This together with the detector 3.75 GHz BW means that quasi-continuous 3.75 GBits/sec pattern can be generated. The word detector operates in reverse principle of Fig. 4a and b and therefore has the same bandwidth limitation. For integration and digital to analog conversion, the BW is determined by the strobing speed of the detector as generated by a shift register or counter which can be as fast as 1 GHz by using ECL logic.

4. CONCLUSION

In summary, the utilization of reflex matrices in GHz signal processing is found to be feasible. The submatrices approach for specific signal processing function is advantageous in that it reduces complexity and cost and increases bandwidth. In the case where the set of signals to be processed does not form a complete set, further reduction in the size of the submatrices is possible. Quasi-DC operation for an a-priori signal processing system is especially attractive because it eliminates the dependence on the speed of external addressing circuits which presents the major deleterious factor. The result is detector limited operation which can be very broadband. With the commercial components discussed here, it is found that GHz operation can be achieved in delay generation, loop filtering, word generation and detection, integration and digital to analog conversion. Other signal processing functions are still possible by rearranging the configuration of the delay lines in the matrices.

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