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2.0 GHz Sampling Rate Transversal Filter

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ABSTRACT

A variable weight transversal filter was used to process analog signals in real time. The length of the delay lines between filter taps determined the sampling rate. The delay lines were made from optical fibers. The variable tap weights were implemented using integrated optical couplers under computer control. An electronic RF signal was input to the transversal filter by externally modulating a laser diode. The RF power out of the transversal filter was measured using a spectrum analyzer. The dynamic range of the filter was found to be greater than 70 dB. The factors which limit the operating performance of the filter were calculated. The actual filter response agreed well with predictions based on computer simulations. This work can be extended up to 16 GHz sampling rates using current technology.

Signal processing systems capable of handling 8 gigahertz bandwidth signals are now realizable using fiber optics and integrated optical devices. In previous work [1–6], transversal filters and lattice filters have been built. Most previously constructed filters suffered the disadvantage of being limited to fixed tap weights. In some of these filters the input signal was tapped out by inducing bending losses at intervals in the fiber [1,3]. By using lattice fiber optic signal processing, some authors [1,7] have demonstrated that several signal processing functions, including filtering, could be performed using directional couplers as tap weights. Another approach used to make fixed weight taps was to produce dielectric mirrors directly in the fiber [6]. All of these systems were limited by the inflexibility of their weighting scheme. This limitation affected the filter performance in two ways. First, the filter could not be reconfigured. This meant that it was not possible to adapt the response function of the filter to meet changes in operating requirements. Second, it was not possible to correct for tap weight errors. When a fiber optic transversal filter is built, by any technique, there are errors due to inconsistencies in the loss and the delay between taps. Fixed tap systems had no technique for self correction of these errors.

The system we will describe was used to process large bandwidth analog electrical signals. The sampling rate was 2.0 GHz. This fiber optic transversal filter could handle higher bandwidth signals and faster tap weight update rates than any electronic competing technology. In contrast to previous optical transversal filters, this filter was reconfigurable. With proper drive electronics the tap weights could be changed at up to gigahertz rates [8]. If a signal is stationary for periods greater than the reconfiguration time, then the tapped delay line can be programmed to perform a sequence of filter operations. For example, we will show how the weights can be changed to do phase independent null steering.

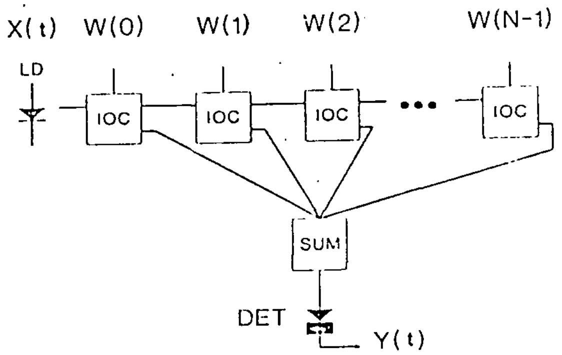

Figure 1. Variable weight fiber optic tapped delay line. (LD-laser diode, IOC-integrated optical 2 by 2 coupler, SUM-incoherent summer).

A simple tapped delay line transversal filter is shown in Figure 1. The response function of this filter is given by:

$$Y(t) = \sum_{k=0}^{N-1} W(k) \cdot X(t-k\tau)$$

where k is the sample number and τ is the sampling period. The 1.3 μm light from a laser diode is intensity modulated by a high bandwidth electric signal, $X(t)$. The light in the fiber is conveyed to a series of integrated optic two-by-two couplers (IOCs). The IOCs serve as filter taps where W(k) is the weight on the k_{th} tap. The intensity of the beam passed by the IOC is controlled by the applied voltage. The remainder of the light is collected by an asymmetric star coupler and directed to a photodetector. The signal at the detector is the incoherent sum of the optical intensities from each tap. The electrical output of the detector is the electrical input signal modified by the tapped delay line filter. The tap weights can be computed either in advance or during the filtering process (i.e., for adaptive signal processing and neural computing applications).

It is difficult to calculate the voltages which accurately bias the IOCs in the transversal filter in Figure 1. This is because the bias voltages depend on the desired weighting function, W(0 to N–1), for the entire filter and on the system losses. In order to simplify the weight calculations, the filter we built used the tapped delay line design shown in Figure 2. With this design, the desired weight value is independent of W(0 to N–1). We predicted the losses in this eight tap system for maximum transmission at each coupler (W(0 to N–1) = 1). For this analysis, we assumed 2 mW of power were coupled from the laser diode into the fiber and used the losses specified for off-the-shelf devices (see Table 1). With these assumptions for the losses, we predicted the signal at the detector would be 11.8 dB down, which corresponds to about 140 μW.

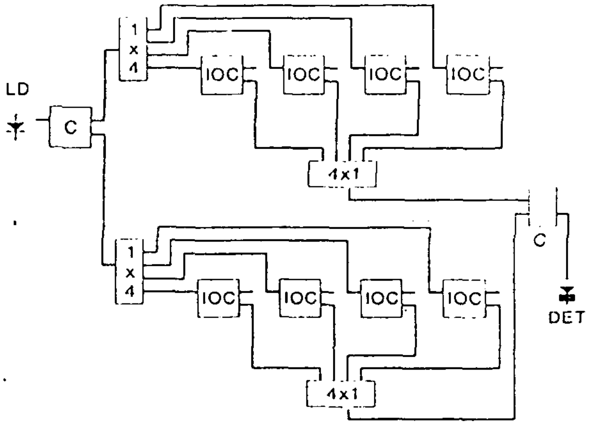

Figure 2. Variable weight fiber optic tapped delay line designed for simplified weight calculation (LD–laser diode, IOC–integrated optical 2 by 2 coupler, C–3dB coupler, 1x4–splitter, 4x1–assymetric star coupler, DET–detector).

TABLE 1

Coupling Losses

Fiber Optic Splice	0.15 dB (typical)
1x4 Tree Coupler	0.6 dB (maximum)
I.O. 2x2 Coupler	6.0 dB (maximum)

The filter we built used a 120 mW OKI laser diode, *BT&D 1x4 trees*, *Crystal Technology 2x2 integrated optical* couplers, Canstar summers, and a Fujitsu InGaAs APD detector. We used 10 cm fiber optic delays. For the group velocity in the fiber, this length corresponded to an effective 2.0 gigasample per second sampling rate. A 0–10 volt control voltage was applied to the integrated optical couplers by either HP voltage supplies, or through an IBM computer controlled SRS interface bus. Since the extinction ratios and bias voltages for each integrated optical coupler were not the same, the computer ramped the voltage on each IOC to find the voltages corresponding to the output intensities. This information was used to normalize the IOCs to one another.

A 0 to 2 GHz signal was used to characterize the response of our transversal filter. The laser modulator and the detector response were not flat throughout this frequency band. A spectrum analyzer corrected for the roll-off in the modulator and detector response so we could examine the actual response of the filter. In order to eliminate possible ambiguities in the interpretation of our data which could arise from the conversions of electrical signals to optical signals, and vice versa, all of our measurements were of RF electrical power in and RF electrical power out.

In order to characterize the filter response, we tested the filter for various combinations of tap weights. For example, we set three taps to unity weights and the rest to 0. The corrected response for this configuration is shown in Figure 3a. Figure 3b. shows a computer simulation of the filter response. The depth of the notch was limited by the noise floor and by our measurement instrumentation. We consistently measure nulls greater than 70 dB from the low frequency signal power. For our experiments, the system noise floor was determined primarily by our detector.

This technology can be applied to various filtering functions. For example, if the filter is designed with a null at a particular frequency, a limited amount of null steering can be achieved by modifying the weights. This type of null steering can be performed without introducing any phase shifts into the modulating signal. In other words, no variable delays are required.

The response function of a three tap transversal filter with unity value tap weights (W(0–2) = 1) has a null at f=fs/3. By changing the tap weight values, the null can be shifted over the entire frequency band. With only positive tap weights, we can shift the null from 1/4 the sampling frequency to 1/2 the sampling frequency.

Transversal filter functions are generally performed electronically using computers and specialized integrated circuits. The maximum signal bandwidth electronic transversal filters can handle is about 100 MHz, and they can be reconfigured in about 1 microsecond. Newer techniques use surface acoustic wave (SAW) devices and active charge transport devices such as CCDs. SAW devices are limited to bandwidths of 40% of the center

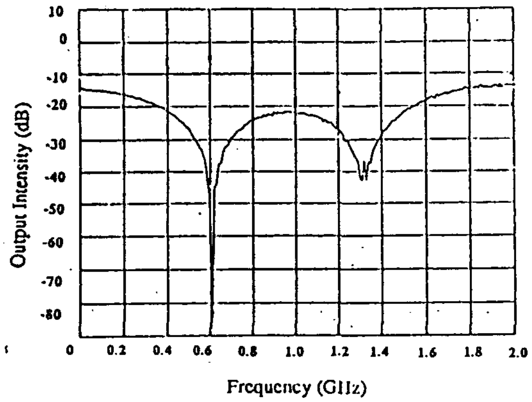

Figure 3a. Output intensity in dB showing the three tap filter response for signals from 0 to 2 GHz.

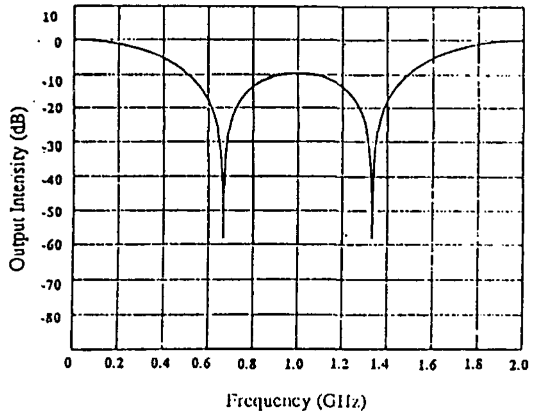

Figure 3b. Computer simulation of three tap filter response. fs = 2 GHz

frequency and CCD devices have bandwidths less than 5 MHz.[9] Tapped delay line transversal filters built using SAW devices are not reconfigurable.

The transversal filter we have described in this paper has the large signal bandwidth of previous fiber optic transversal filters. It also has the large dynamic range and versatility of an electronic system. This technology is most useful for high bandwidth signal processing applications.

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