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Null shifting with fixed delays

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ABSTRACT

We demonstrate null shifting over a 1 GHz bandwidth using a fiber optic and integrated optic transversal filter. The null depth for our system is greater than 70 dB measured with a 10 KHz IF bandwidth. The null shifting is achieved by varying the tap weight values. Null shifting in the response of a transversal filter is directly related to null steering for a radar direction finder. The fixed delays consist of optical fibers cut at 10 centimeter increments. Integrated optical 2x2 couplers are used as the tap weights. The weighting is controlled by an applied voltage. The depth of the null is limited by the dynamic range of the source/detector combination. Ordinary fixed weight fiber optic transversal filters are subject to dynamic range and bandwidth limitations due to errors in cutting the fiber lengths. This problem can be remedied by using variable taps to shift the null frequency. The null depth and resolution is not detrimentally 'fected by using this approach.

I. INTRODUCTION

Fiber optics and passive optical devices have low insertion loss over a large bandwidth. Several efforts have been made to take advantage of the characteristics of fiber optics to solve some phased array radar problems. For example, fiber optic delay lines are used in phased array radar to do direction finding.[1] Usually the angular response of the antenna array is controlled by the delay line lengths. Recently, some groups have developed new techniques for varying the delays.[2,3] Although the delay lines can change the angle of peak response of the direction finder, they can not change the shape of the response or the relative location of nulls.

In this paper, we present null shifting results for a fiber optic FIR filter using variable tap weights. The performance of this filter relates directly to the performance of a radar direction finder or beam former. Frequency null shifting in the filter corresponds to changing the nulls in the angular response of a direction finder. A diagram of a fiber optic FIR filter and a diagram of a fiber optic direction finder are shown in Fig. 1. Both systems consist of weighted fiber optic delay lines. The difference in the delay line lengths, $\Delta \ell$, determines the sampling frequency, f_s, of the filter, or the angle of arrival for peak response, θ_0, for the direction finder. The relationship between these quantities is given in equation (1)

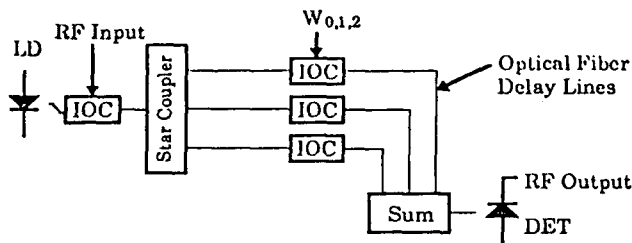$$\Delta \ell = \frac{c}{f_s n_g} = \frac{d \sin \theta_0}{n_g} \qquad (1)$$
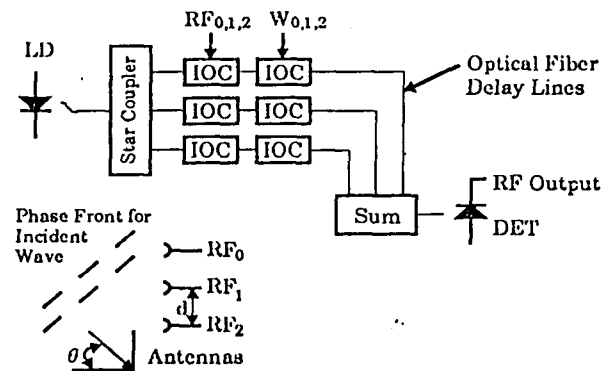
Fig. 1a. FIR filter implementation.

Fig. 1b. Direction finder implementation.

where n_g is the group index of the optical fiber, and d is the separation between antenna elements. τ_s is the sampling period, $1/f_s$. The major difference between the construction of the two systems is that the FIR filter has only one signal input, whereas the direction finder has a separate input from each element of the antenna array.

2. EXPERIMENT

The filter was a basic transversal filter with taps and delay lines as shown in Fig. 1a. The response function of this filter is given by:

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

(2)

Y is the filtered output, W is the value of the kth tap weight, and N is the number of taps.

The laser source was a 1.3 μm laser diode (LD) operating at 48 mW CW output power. The input signal, X, was introduced by RF modulating an integrated optic two by two coupler (IOC). The intensity modulated output was coupled into seven different taps via 3 dB fiber couplers and 1x4 trees. The fiber optic delay lines were cut so the differences in length were as near as possible to 10 centimeters. For the fiber group velocity, n_g, 10 cm corresponded to an effective sampling frequency of 2 GHz.

Each tap of the FIR filter was weighted by a different IOC. Only one input and one output of each IOC was used for this application. The intensity of the light passed by the IOC was controlled by an applied voltage. The weighted signals were collected by an asymmetric star coupler and directed to an InGaAs avalanche photodetector (DET). The signal, Y(t), at the detector was the incoherent sum of the optical intensities from each tap. The intensity passed by each tap was measured separately. Then the bias voltages were set so the filter weights were normalized to

the tap with the lowest maximum output power. Computer controlled voltage supplies were used to automate this process.

A network analyzer was used to characterize the filter response. The IOC used to modulate the laser beam and the high speed detector both had some roll off in their response to high frequency signals. We corrected for the modulator/detector high frequency roll off in all of our measurements of the FIR filter response. The correction was done by dividing the FIR filter response spectra by the modulator/detector spectrum. Although this technique eliminated the roll off problem, the laser diode, modulator, and detector noise were not eliminated.

The corrected response of a FIR filter (weights: $W_0=W_1=W_2=1$ and $W_{3-6}=0$) is shown in Fig. 2a. The dotted line shows the computer simulation of the response of a perfect filter with these weights is also shown in Fig. 2a. The computer simulation assumes exactly 10 cm length differences and complete extinction at the unused IOCs; W_{3-6}. The discrepancy between the actual null frequency and the predicted null frequency of one third the sample frequency is due to errors in cutting the fiber lengths. An adjustment of the weights can be used to correct for this discrepancy as shown in Fig. 2b. Here the middle tap weight, W_1, was varied until the filter response matched the computer prediction. Details of this process are discussed below.

3. Null Shifting Technique

The variable weights in this FIR filter made it possible to shift the frequency of the nulls in the filter response. In most fiber optic and analog systems null shifting is achieved by changing the delay between taps or by changing the phase of the tap weights. However, null shifting can also be done with real weights.
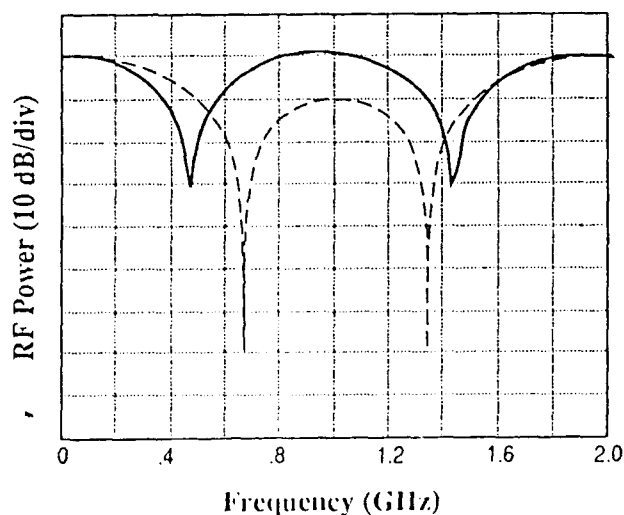

Fig. 2a. Frequency response of the three tap filter. Tap weights close to unity (solid curve) and computer simulation (dotted curve).
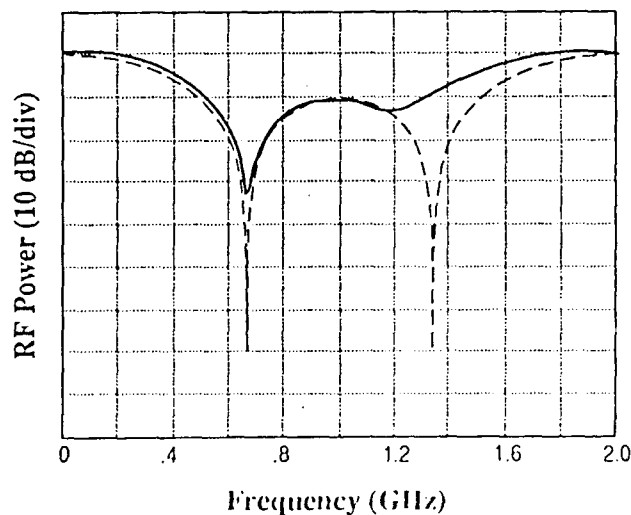
Fig. 2b. Frequency response of the three tap filter. Tap weights adjusted (solid curve) in order to shift null to coincide with computer simulation (dotted curve).

The transfer function of an N tap transversal filter (in the frequency domain) is given by the expression:

$$H(f) = \mathscr{W}_0 + \mathscr{W}_1 e^{-i2\pi f \tau_s} + \mathscr{W}_2 e^{-i2\pi 2f \tau_s} + \dots + \mathscr{W}_{N-1} e^{-i2\pi Nf \tau_s} \tag{3}$$

where $\mathscr{W}_i$ are dummy weights. In general, the weights can take on real or imaginary values where imaginary values represent phase shifts. In a fiber optic transversal filter the weights are all real. As an example, we will describe how the weights are chosen to set one null for a three tap filter. The calculations for larger filters are similar. When the number of filter taps, N, is odd, then $(N-1)/2$ nulls can be independently controlled. If N is even the one null is always fixed at $f_s/2$ and the number of independently controlled nulls is $(N-2)/2$. To find the weight values which will give real nulls at any arbitrary frequency, f_n, we need to solve equation (3) for $H(f_n) = 0$. Since we do not want any solutions that require complex weights, we separate (3) into two different equations.

$$0 = \mathscr{W}_0 + \mathscr{W}_1 \cos(x) + \mathscr{W}_2 \cos(2x) \tag{4a}$$

$$0 = \mathscr{W}_1 \sin(x) + \mathscr{W}_2 \sin(2x) \tag{4b}$$

In these equations $x \equiv 2\pi f_n \tau$. Since only the relative values of the weights are important, we can set one of the weights to an arbitrary constant to scale the solution. We choose to set $\mathscr{W}_2 = 1$. Then the solutions are:

$$\mathscr{W}_0 = 1, \quad \mathscr{W}_1 = -\frac{\sin(2x)}{\sin(x)}, \quad \text{and } \mathscr{W}_2 = 1. \tag{5}$$

Since the absolute value of the weights can not exceed 1, we must normalize the weights separately for each null frequency we select. The normalizations are calculated using $MAX = \text{maximum } \{|\mathscr{W}_0|, |\mathscr{W}_1|, |\mathscr{W}_2|\}$. The new weights are:

$$W_0 = \frac{\mathscr{W}_0}{MAX}, \quad W_1 = \frac{\mathscr{W}_1}{MAX}, \quad \text{and } W_2 = \frac{\mathscr{W}_2}{MAX}. \tag{6}$$

These solutions are plotted versus desired null frequency in Fig. 3. We find that with only three filter taps, the null can be shifted over the entire frequency band with positive and negative tap weights. With only positive tap weights we can shift the null from 1/4 the sampling frequency to 3/4 the sampling frequency. We checked the theoretical results experimentally using only three taps of our FIR filter. We set the first and third tap to $W_0 = W_2 = 1$, and we increased the middle tap weight from $W_1 = 0$ to $W_1 = 1$. The experimental data is shown in the frequency range from 500 to 667 MHz in Fig. 3

We have demonstrated how a null can be placed at any arbitrary frequency by controlling the weights of a three tap filter. Similarly, two nulls can be placed at two different arbitrary frequencies with a 5 tap filter, etc. A consequence of these results is that null shifting can be performed for large bandwidth signals and high sampling rates using fiber optic techniques. Filter null shifting is directly analogous to null steering in a radar direction finder. It is not possible to change the angle of peak response of a radar direction finder with fixed delays. However, it is possible to control the nulls.

4. DISCUSSION

Beamforming and direction finding can be performed on high bandwidth radar signals using fiber optic delay lines. By using variable weights, we have circumvented the usual limitations i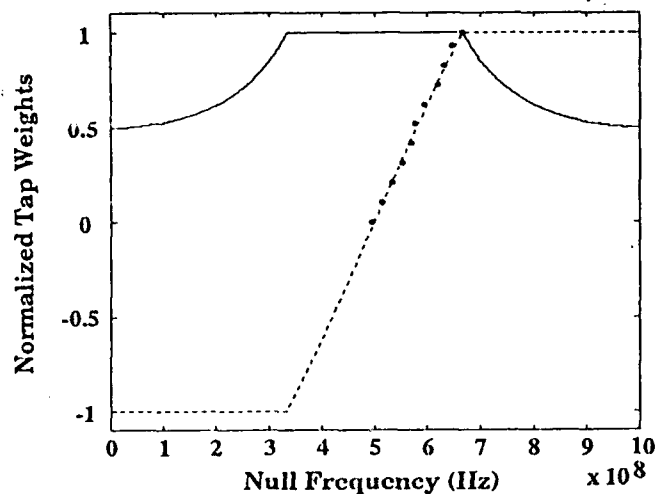mposed on direction finders with fixed delays. The angle of peak response of the direction finder is determined by the delay lines, whereas the null angles depend on the weights. A change in null frequency in the FIR filter response is related to the change in the angle of the direction finder null. The weights can be used to sweep a null in the angular response of a direction finder through 180°. Unfortunately, the null angle is RF frequency dependent. Similarly, the direction finder delay lines can be used to change the angle of peak response. If a system were constructed which implemented both variable delay lines and variable weights, the response of the direction finder for RF frequency and incident angle could be better controlled.

Fig. 3. Demonstration of null frequency shifting by varying center tap weight (dotted curve) with first and third tap weight held constant (solid curve).

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