All-Optical RF Filter Using Amplitude Inversion in a Semiconductor Optical Amplifier

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***Abstract*—We present an all-optical delay-line radio-frequency (RF) notch filter. The filter exploits cross-gain modulation in a homogeneously broadened laser medium to obtain a negative tap in an optically incoherent system. Applications including moving-target indication (MTI) in optically controlled radars are discussed.**

***Index Terms*— Feed forward filter, microwave photonics, optical signal processing, MTI, semiconductor optical amplifier (SOA).**

I. Introduction

SIGNAL processing using optic-fiber delay lines is a very powerful technique for processing high bandwidth signals [1] . Optic fiber is an excellent propagating medium for time delays. It has low loss, low dispersion, light weight, and is inexpensive. Moreover, the signal carried by the intensity-modulated optical beam is insensitive to electromagnetic radiation.

Various optical delay-line configurations have been proposed to achieve different radio-frequency (RF) filter functions. These configurations can be either optically coherent [2], [3] or incoherent [4]–[6]. Coherent optical processing allows more flexibility in shaping of the filter-transfer function because negative tap weights are possible. Nevertheless, the phase of the optical beam has to be precisely controlled since the filter is highly sensitive to any phase variation. Moreover, the longest time delay in the filter has to be shorter than the coherence time of the optical source.

Incoherent processing does not require any control of the optical phase. The filter is, therefore, less sensitive to external perturbation (e.g., variation of temperature). Long time delays are made possible, but the shortest delay line has to be longer than the coherence length of the optical source. Most important, only positive taps weights are possible since the intensity is a positive quantity. To overcome this limitation, an optoelectronic approach using differential detection has been proposed [1], [7] and experimentally demonstrated [8]. In this approach, optical signals are detected using a pair of matched photodetectors and combined electrically.

In this paper, we propose and demonstrate a new technique to realize negative weights in optical-fiber filters. The filter maintains the advantages of incoherent operation but does not require optoelectronic conversion in order to attain negative weights. Negative weighting is obtained using signal inversion in a semiconductor optical amplifier (SOA). Due to gain saturation in the homogeneously broadened gain medium of the SOA [9], an inverted copy of an RF-modulated optical beam at wavelength λ_1 appears on a probe signal at wavelength λ_2 [10]. Upon combining using an optical coupler, the ac components are subtracted (in the optical domain). Thus, the SOA performs the function of a negative tap. Due to the wavelength conversion, any time delay can be used regardless of the coherence length of the optical source. The main advantage of this technique compared to differential detection is that the signal is kept in the optical domain, which allows cascading to attain higher order filters. In this paper, we demonstrate a single delay-line canceller where an RF signal is subtracted from its delayed version in the optical domain. Two different configurations of the filter are proposed and their performance is discussed in terms of linearity. Application for moving-target indication (MTI) in optically controlled radar technology is also discussed.

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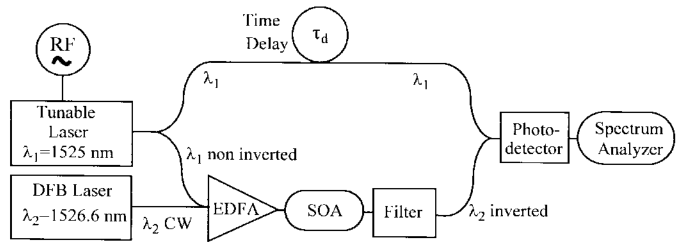

Fig. 1. Schematic representation of the filter—a directly modulated laser beam is split into two parts. One part is combined with a CW beam at λ_2, both beams are then amplified in an EDFA and sent to an SOA. The negative tap at λ_2 is then combined with the delayed positive tap at λ_1 and detected inside the same photodetector.

II. All-Optical Filter Approach

Fig. 1 describes the schematic of the filter. An external-cavity tunable laser operating at $\lambda_1 = 1525$ nm is directly RF intensity modulated. The coherence length of the laser is on the order of 1 km. This beam is then split into two parts, one part goes to the long time delay consisting of 500 m of optic fiber. The other part is combined with a continuous wave (CW) beam from a distributed feedback (DFB) laser operating at $\lambda_2 = 1526.6$ nm. These beams are then amplified in an erbium-doped fiber amplifier (EDFA) and sent into the SOA. Due to cross-gain modulation in the SOA, the emerging signal at λ_2 represents the inverted version of the RF signal

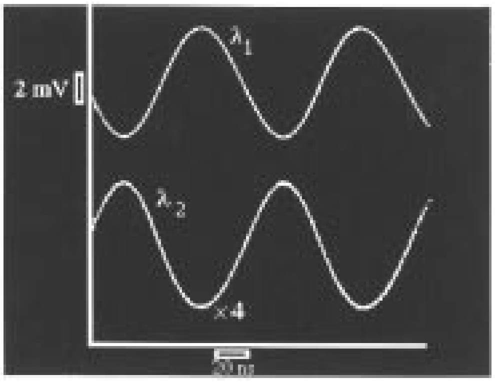

Fig. 2. RF signals at the output of the SOA and the filter showing the inversion. Upper trace is the signal at λ_1 and the lower trace is the wavelength converted/inverted signal at λ_2.

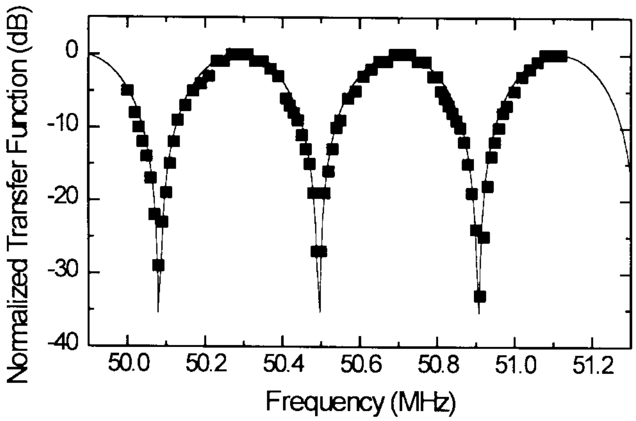

Fig. 3. Normalized transfer function of the filter for the fundamental peak. Points are the experimental data and the solid line is the theoretical prediction (1).

at λ_1. At the output of the SOA, the noninverted signal at λ_1 is filtered out using an arrayed-waveguide grating filter. The inverted signal is then combined with the signal at λ_1 which is delayed by the long time delay.

Fig. 2 shows the amplitude inversion of the RF signal performed by the SOA. The input to the SOA is a 10-MHz signal at λ_1 and a CW signal at λ_2. An increase in the photon density at λ_1 reduces the carrier density inside the SOA due to stimulated emission. Since the SOA is a homogeneously broadened medium, the carrier density is reduced throughout the entire gain spectrum [9]. Thus, the optical gain at λ_2 is reduced, and the intensity of the light at this wavelength decreases. The RF signal at λ_2 is, therefore, an inverted copy of the signal at λ_1, as seen in Fig. 2. Thus, a broad-band negative tap is obtained in an optically incoherent regime. The inversion process can be achieved from dc to the maximum frequency response of the SOA. Wavelength conversion of digital signals of up to 20 Gb/s has been demonstrated using this technique [11]. The SOA used in this experiment was polarization sensitive. Nevertheless, a polarization-insensitive SOA [12] can be used to avoid the polarization dependance.

Fig. 3 shows the normalized transfer function of the filter for the fundamental peak. The filter response is a maximum when the two RF signals are in phase and it is a minimum

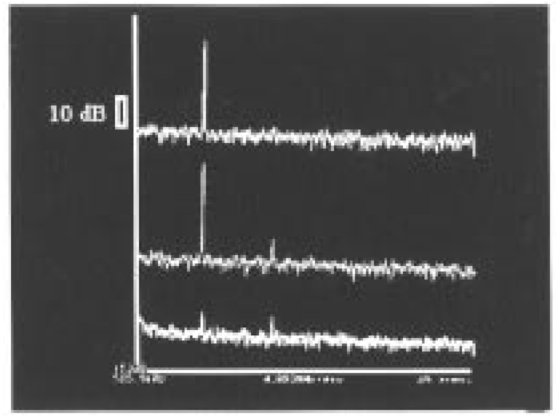

Fig. 4. Spectrum of the signals at λ_1 (upper trace) and λ_2 (middle trace) before recombination. The lower trace is the spectrum after filtering for a fundamental frequency corresponding to a null frequency of the filter.

when they are exactly π out of phase. The periodicity of the filter is determined by the time delay τ_d. Since the two intensity modulated signals are subtracted, the normalized transfer function represented by the solid line in Fig. 3 is described by

$$T(f) = |\sin(\pi f \tau_d)|. \tag{1}$$

Null frequencies are then given by

$$f_k = \frac{k}{\tau_d} \tag{2}$$

where $k = 0$ or any positive integer. The transfer function is $\pi/2$ phase shifted compared to the case where the two signals are added [13]. The maximum null attainable is limited by imbalance in signal intensity in both arms. The amplitude in the arms can be controlled with attenuators or by changing the bias point of the SOA (current or optical input power).

III. Experimental Results

One of the concerns in using the SOA for analog-signal applications is signal distortion [14], [15]. Due to nonlinearities of the gain saturated medium, higher harmonics of the input signal are created. The amount of distortion is strongly dependant on the operating point of the SOA (input power level at λ_1 and λ_2, wavelengths used compared to the residual Fabry–Perot mode of the SOA, modulation depth, etc.) [14]. We have investigated the effect of SOA nonlinearity on the performance of the filter. Fig. 4 represents the spectrum of the signal at different points in the filter. The top trace represents the frequency response for the signal at λ_1, before entering the SOA. The fundamental peak is at the modulation frequency of 10.29 MHz and corresponds to a null frequency of the filter. No higher harmonic-distortion peak is visible in the spectrum of the signal. The middle trace in Fig. 4 represents the spectrum for the signal after wavelength conversion by the SOA. Due to the nonlinearities in the SOA, a second harmonic is present. The bottom trace is the spectrum at the output of the filter (after subtraction). The fundamental peak is strongly reduced and the residual peak at this frequency is due to a small mismatch in the amplitude of the two signals in both arms. The second harmonic peak remains unchanged because

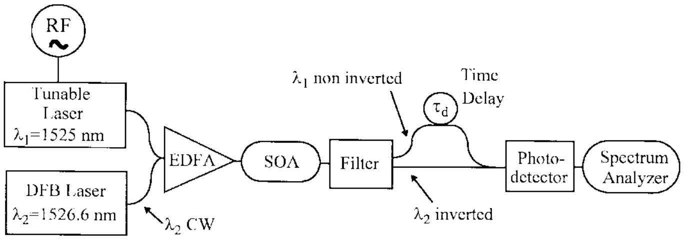

Fig. 5. Schematic representation of the differential configuration of the filter, showing improved performance. Beams at λ_1 and λ_2 go through the SOA. The positive tap at λ_1 is delayed and is recombined with the negative tap at λ_2. Both beams are then detected in the same photodetector.

the signal is only distorted in the lower arm. In this filter configuration, the distortion of the signal by the SOA is the limiting factor for the complete cancellation of the signal.

To reduce the effect of distortion, a second configuration of the filter was investigated. In this configuration, shown in Fig. 5, the intensity modulated signal at λ_1 and the CW beam at λ_2 are combined, amplified by the EDFA, and sent into the SOA. Signals are then separated by the arrayed waveguide grating filter and the λ_1 component is delayed by the long time delay τ_d. Both signals are then combined and sent into the photodetector. Fig. 6 shows the spectrum of the signal at λ_1 (upper trace) and λ_2 (middle trace) after their separation by the optical filter. Since both signals go through the SOA, both experience similar distortion. The bottom trace in Fig. 6 shows the spectrum at the output of the filter. As can be seen, both the fundamental peak and second harmonic are strongly reduced. This interesting behavior stems from the fact that harmonics of the signal which are created inside the SOA are also inverted for the signal at λ_2 and are thus subtracted. However, as the amount of distortion inside the SOA (ratio of the harmonic peak over fundamental peak) is not the same for the original signal at λ_1 and the wavelength converted signal at λ_2, harmonic distortion cannot be completely removed. The degree of reduction depends on the exact bias point of the SOA. Fig. 6 shows a reduction of the second harmonic peak of more than 7 dB compared to the first configuration shown in Fig. 4. Higher harmonics which do not appear in Figs. 4 and 6 will be similarly reduced leading to an improvement of the performance of the filter. The second configuration also has the advantage of amplifying both signals inside the SOA. The signals are, therefore, regenerated while being processed.

In addition to removing nonlinearities created in the SOA, the filter is able to remove any higher order harmonics which may be created at the modulation level (either direct modulation of the laser or external modulation). Since multiples of a null frequency are also null frequencies (2), harmonics which are created during modulation are also inverted by the SOA and are filtered out when the fundamental frequency corresponds to a null frequency of the filter. This is in contrast with the version of the filter where the two intensity-modulated signals are added [13]. In this latter case, odd multiples of a null frequency are not null frequencies. Therefore, when the fundamental peak is filtered out, the second harmonic peak and higher even-order harmonics created at the modulation level are preserved.

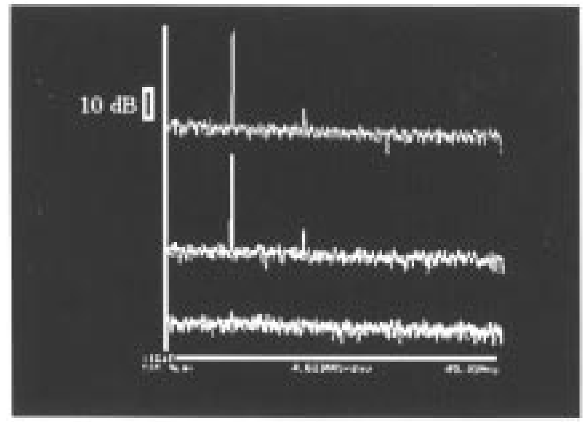

Fig. 6. Spectrum of the signals at λ_1 (upper trace) and λ_2 (middle trace) before recombination using the differential configuration of the filter, and spectrum after filtering for a fundamental frequency corresponding to a null frequency of the filter (lower trace).

The fact that distortion can be reduced is important for the dynamic range of the system. The dynamic range is limited in its lower limit by the shot noise at the photodetector and in its higher limit by nonlinearities in the different active components of the system. A reduction of the effect of distortion directly leads to an improvement of the dynamic range of the filter.

Another unique advantage of the filter is that the two signals which recombine inside the photodetector are at two different wavelengths avoiding problems of optical coherence which appear in traditional delay-line filters [16]. Moreover, noise due to the random phase noise of the laser will appear at the beat frequency of the two optical beams instead of appearing at the baseband, as in the case when a single wavelength is used [17]. In our experiment, the wavelength difference $\lambda_2 - \lambda_1$ is 1.6 nm, which corresponds to 200 GHz. Therefore, a laser's phase noise centered at this frequency will be averaged to zero due to the finite bandwidth of the photodetector. This is a unique advantage afforded by the wavelength conversion process.

A major application of the feed forward filter is in radar technology. In MTI radar, the small echo from the target has to be distinguished from the large echo from fixed objects (clutter). In a typical radar system, this filtering is digitally realized after down conversion to baseband and analog-to-digital (A/D) conversion [18]. Typically, 14–18 b of resolution are required in order to resolve the faint target from the strong clutter. If some filtering is performed in the analog domain before A/D conversion, the requirement on A/D resolution will be relaxed. For example, with a 30-dB attenuation of the clutter in the analog domain (see Fig. 3), the required A/D resolution is reduced by 5 b. Optical filters are ideal to perform this filtering function at the front end of the antenna as they are compatible with the emerging technology of optically controlled phased-array antennas, and long low-cost time delays are easily achieved.

The filtering of the clutter in a typical MTI radar system is performed by delaying a returned pulse by the pulse period, and subtracting it from the following pulse, as shown in Fig. 7.

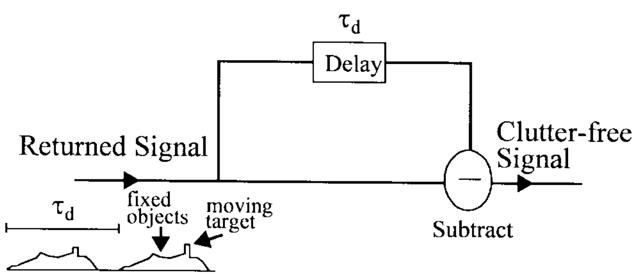

Fig. 7. Schematic of an MTI radar in which the pulse is delayed by the pulse period and subtracted from the following pulse.

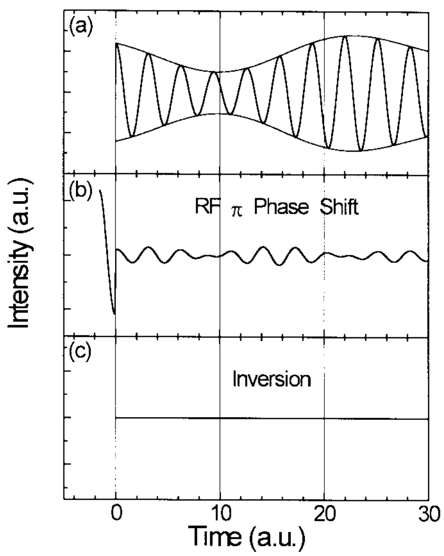

Fig. 8. (a) Time-domain representation of a radar pulse. (b) Resulting filtered signal after filtering using π phase shift of an RF carrier—due to the π phase shift the cancellation is incomplete. (c) Resulting filtered signal after filtering using inversion inside an SOA—the cancellation is theoretically complete.

The clutter which has the same phase from pulse to pulse will be removed, while the Doppler shifted-target echo will be preserved. All-optical subtraction is, therefore, a key operation of the filtering function.

In principle, subtraction in the analog domain can also be made by shifting one of the signals by half the RF period (π out of phase) and then combining them. However, for MTI radar this technique does not lead to a perfect cancellation of the clutter as analytically shown in Fig. 8. Fig. 8(a) represents the simulated pulse of a radar, which consists of an RF signal amplitude modulated. Fig. 8(b) shows the filtered signal after recombination of the signal represented in Fig. 8(a) with a RF π phase-shifted version of itself. Although a strong attenuation is achieved, part of the signal still remains. The nonperfect cancellation stems from the fact that a π phase shift is not necessarily equivalent to an inversion. In contrast, Fig. 8(c) shows the cancellation when the signal represented in Fig. 8(a) is recombined with an inverted version of itself. A theoretically perfect cancellation is obtained.

The difference between these two techniques will depend on the relative frequency of the RF signal compared to the slow modulation on top of the return pulse. At high RF frequencies, the small extra time delay introduced to perform the π phase shift will become negligible compared to the typical period of the intensity modulation. Therefore, the difference between inversion and π phase shift will not be significant. However, at lower frequencies, the extra time delay introduced to perform the π shift may become comparable to the typical period of the intensity modulation, leading to a nonideal cancellation of the clutter. In this case, inversion of the signal using cross-gain modulation inside the SOA is critical for the filtering process.

The RF frequency at which the filter is operating will determine the performance of the filter. At high frequency, π phase shift using a small extra time delay can perform a good cancellation of the clutter. However, at these high frequencies the stability of the filter will become an important issue. Small variation of the time delay introduces a nonnegligible shift of the null frequency (shift in the null frequency being proportional to the RF frequency [19]). The small variation of the null frequency can be due, for example, to a small change of temperature or vibration inside the fiber [20]. Temperature control of the long delay-line optic fiber would, therefore, be necessary for these high frequencies. To overcome these problems, optical filtering must be done after down conversion to IF. At these lower frequencies, inversion inside the SOA is essential to achieve ideal cancellation of the clutter.

IV. Conclusion

We have proposed and demonstrated a new all-optical notch filter. Cross-gain modulation in a homogeneously broadened laser medium is used to obtain a negative tap in an optically incoherent system. Thus, the filter is able to perform subtraction of intensity-modulated signals while being optically incoherent. Limitation of the filter due to distortion inside the SOA is discussed and it is shown that it can be reduced using a differential configuration of the filter. This all-optical notch filter can be used in MTI technology to filter out the clutter signal. It can be used to filter the clutter at intermediate frequency (IF) in the analog domain prior to A/D conversion, thus alleviating the requirement for high-resolution A/D converters. Moreover, as the signal stays in the optical domain, cascading of delay-line processors is made possible.

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