Tunable all-optical negative multitap microwave filters based on uniform fiber Bragg gratings

J. Mora, M. V. Andrés, and J. L. Cruz

Instituto de Ciencia de los Materials, Universidad de Valencia, Dr. Moliner 50, 46100 Burjassort (Valencia), Spain

B. Ortega, J. Capmany, D. Pastor, and S. Sales

Instituto de Informatica, Multimedia, Communicacion y Computadors, Departamento de Comunicaciones,
Universidad Politécnica de Valencia, Camino de Vera, s/n 46022 Valencia, Spain

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We present a novel and simple technique for obtaining transversal filters with negative coefficients by using uniform fiber Bragg gratings. We demonstrate a wide tuning range, good performance, low cost, and easy implementation of multitap filters in an all-optical passive configuration in which negative taps are obtained by use of the transmission of a broadband source through uniform Bragg gratings.

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Fiber-optic transversal filters have attracted the interest of many research groups during the past several years because of their applications in the processing and switching of wideband rf, microwave, and millimetric signals directly in the optical domain. Various kinds of coherent and incoherent optical processing to obtain a large degree of flexibility in the shaping of the filter transfer function have been proposed. Coherent optical processing gives precise control of the optical phase that can be used to generate negative tap weights, which are necessary for obtaining negative-tap transversal filters, whereas incoherent optical processing is insensitive to any phase variation. Therefore several means to overcome this limitation have been reported. The first one was an optoelectronic approach that uses differential detection[1]; other proposals for all-optical configurations with active elements to generate negative taps[2–5] followed. One can use cross-gain modulation in the homogeneously broadened medium of a semiconductor optical amplifier to obtain a negative tap[2]; distortion inside the semiconductor optical amplifier and elevated costs are the main drawbacks of this method. Other configurations have been used to demonstrate incoherent negative-tap transversal filters, such as those that use a carrier depletion effect in a distributed-feedback laser diode,[3] cross-intensity modulation of the longitudinal modes of an injection-locked Fabry–Perot laser diode,[4] and a low-cost wavelength converter based on cross-gain modulation of the amplified spontaneous emission spectrum of a semiconductor optical amplifier.[5]

In previous optical configurations the experimental scheme became complicated and required active components, showing a limited tuning range and permitting implementation of only a two-tap negative filter. Here we propose a new passive and incoherent method for obtaining transversal filters with various negative coefficients. We generate negative taps by using the output signal of a broadband optical source when it has been transmitted by uniform fiber Bragg gratings (UFBGs). The positive taps are independently provided by a laser array, and therefore a high tuning range can be demonstrated in these novel filters.

In our proposal the ideal arrangement of a two-tap filter with one negative coefficient is based on the use of a narrow source with emission frequency at ω_1 and a signal transmitted by a notched optical filter that suppresses frequency ω_2, illuminated by a uniform broadband optical source. The two optical signals are combined in a directional coupler (see the inset of Fig. 2 below). Ideally, spectral distribution $S(\omega)$ can be represented by

$$S(\omega) = P_0\delta(\omega - \omega_1) + P_0[\Theta(\omega) - \delta(\omega - \omega_2)], \quad (1)$$

where P_0 is a constant, $\delta(\omega)$ is the Dirac function, and $\Theta(\omega)$ is the spectral distribution of the broadband source, which is $\Theta(\omega) = 1$ in the ideal case.

The resultant signal of Eq. (1) is modulated in an external electro-optic modulator at radio frequency f ($\Omega = 2\pi f$) and driven to a linear dispersive element. The rf signal is generated and measured by a light-wave component analyzer (LCA). We calculate the filter transfer function by substituting Eq. (1) into Eq. (4) of Ref. 6 to obtain

$$|H(\Omega)| = \Re\left[2P_0 \left|\sin\left(\frac{\Delta\tau\Omega}{2}\right)\right| + P_T\delta(\Omega)\right]^2, \quad (2)$$

where $\Re$ is the photodiode's responsivity. The time delay value that corresponds to the signal is $\Delta\tau = D\Delta\omega$, where D is the delay slope of the dispersive element and $\Delta\omega$ is the separation frequency between taps.

We can identify the first term in Eq. (2) as the negative two-tap filter. In Fig. 1 we show the theoretical transfer function versus rf normalized to $f_0 = 1/(D\Delta\omega)$, where f_0 is the free spectral range (FSR). A phase shift of $\pi/2$ is observed between the two-tap filter with positive coefficients and function

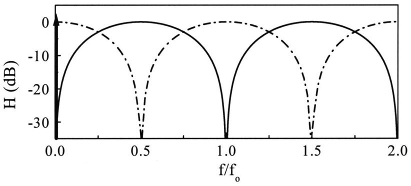

Fig. 1. Theoretical transfer function for a two-tap filter: filter with one negative tap (solid curves) and filter with no negative taps (dotted–dashed curves).

$|H(\Omega)|$, which corresponds to a filter with one negative coefficient. The second term in Eq. (2) introduces a dc signal. That signal comes from the total optical power of the spectral distribution that is driven to the LCA and is proportional to the total optical power P_T of the broadband source. If the optical source has a finite bandwidth, $\delta\omega$, for example, with a Gaussian shape, then the additional term $P_T\delta(\Omega)$ broadens up to a frequency f_c, given by $f_c \approx 1/(D\delta\omega)$, which we can reduce by using higher dispersion values D and broader-band sources. Therefore the system introduces a spurious signal at low frequencies, which can be filtered by use of an electric filter in the system receiver.

To demonstrate our proposal we implemented three filters. The first is a filter formed by a tunable laser (TL) and a signal transmitted by a UFBG, which is illuminated with the amplified spontaneous emission of an erbium-doped fiber amplifier. The broadband optical source has a 3-dB bandwidth of 5 nm near 1530 nm when the injected current is 150 mA. The UFBG is 1 cm long and is written on photosensitive fiber; its Bragg wavelength is 1530.96 nm, its 3-dB bandwidth is 0.15 nm, and it has maximum reflectivity of 8 dB. The use of UFBGs as selective filtering elements in fiber-optic transversal filters was demonstrated and analyzed previously.[6] The light transmitted through the UFBG and the emission of the TL are driven to a 90/10 optical coupler. The combined signal can be monitored by an optical spectrum analyzer by use of the 10% arm. The 90% arm's signal is amplitude modulated in the electro-optic modulator. A fiber length of 23 km will be the dispersive element in the filter, so $D = \beta L_F$, where β is the linear dispersion [15.5 ps/(nm × km) at 1530 nm] and L_F is the fiber length. Finally, the transfer function of the filter is measured in the LCA (see Fig. 2).

To show the tunability of the system, we plot the experimental transfer functions of two rf filters with different free spectral ranges (FSRs) (Fig. 3). We can see that the negative filter response appears above $f_c = 0.58$ GHz, i.e., when the spurious low-frequency term is negligible. The separation wavelengths between the TL and the UFBG are 2.56 and 0.54 nm, corresponding to FSRs of 1.09 and 5.15 GHz, respectively. We must point out that the spectrum shown in the inset of Fig. 2 was measured with a resolution of 0.1 nm and is indicative only of tap positions; in the experiment, the power level of the laser was adjusted to the total power reflected by the grating and to compensate for possible wavelength and polarization dependent loss in the system, so the peak powers of gratings and laser are not identical.

Figure 4 gives the FSR of the negative transversal filter versus several wavelength spacings between the central Bragg wavelength of the UFBG and the TL output signal. The filled squares correspond to the measured FSR of the filter, and the solid line is the theoretical prediction. According to our previous findings,[6] this frequency range can be increased significantly. The experimental slope is 2.80 ± 0.04 GHz × nm, according to the delay slope, 357 ps/nm at 1530 nm, of the dispersive element.

In a second experiment and to show the good performance of these filters when several taps are added, we

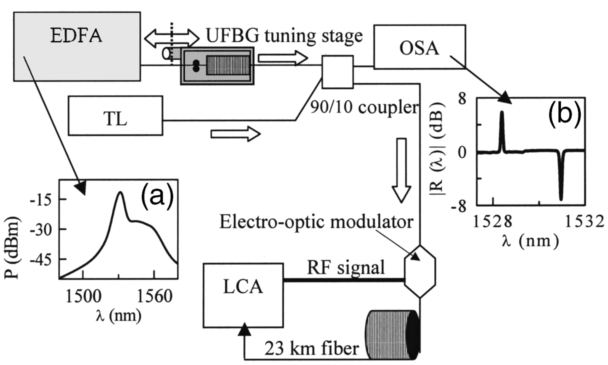

Fig. 2. Schematic of the rf negative-tap filter: OSA, optical spectrum analyzer; other abbreviations defined in text. Inset (a), output power of the broadband optical source, an erbium-doped fiber amplifier (EDFA). Inset (b), input signal launched into the electro-optic modulator relative to the EDFA power level.

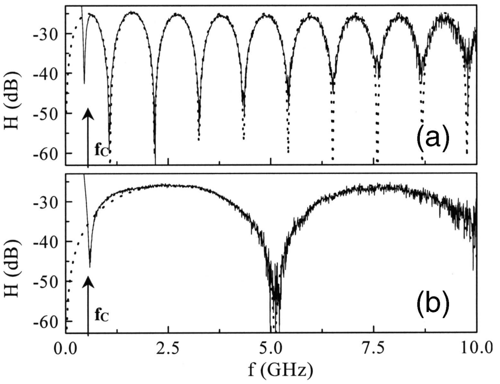

Fig. 3. Filter response versus rf signal frequency for two different FSRs: (a) 1.09 GHz, (b) 5.15 GHz. Theoretical calculation (dotted curves) and experimental results (solid curves).

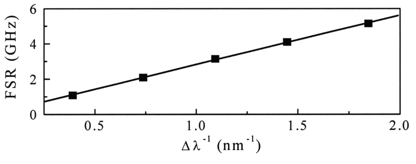

Fig. 4. FSRs of the rf filters versus the reciprocal of the wavelength spacing between taps. Theoretical calculation (solid line) and experimental results (filled squares).

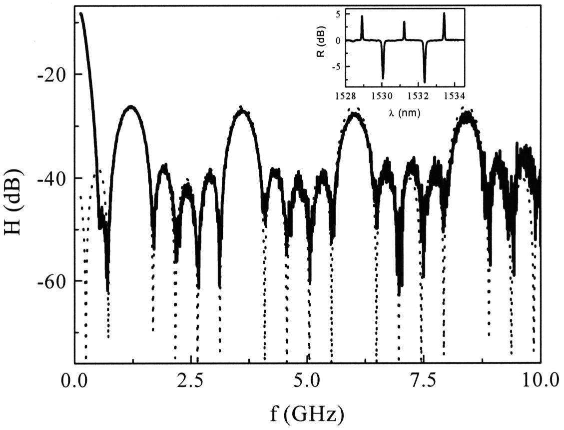

Fig. 5. Filter response versus signal's rf with 1.16-nm equispaced taps near 1530 nm. Theoretical calculation (dotted curves) and experimental results (solid curves). Inset, spectral positions of the five taps.

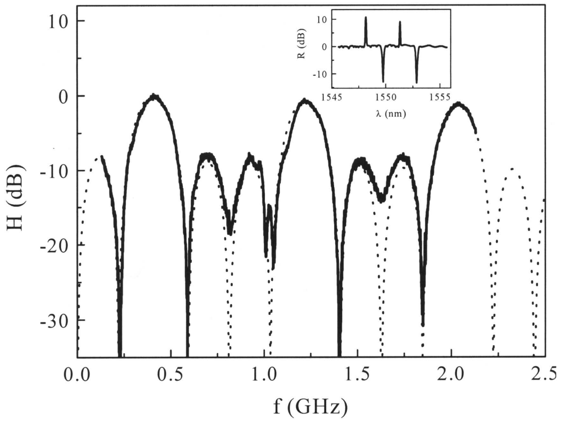

Fig. 6. Filter response versus signal's rf with 1.56-nm equispaced taps near 1550 nm. Theoretical calculation (dotted curves) and experimental results (solid curves). Inset, spectral positions of the four taps.

implemented a five-tap rf filter, using two UFBGs and three lasers with a wavelength separation of 1.16 nm (Fig. 5). The FSR is 2.40 GHz, and the 3-dB bandwidth is 0.437 GHz.

The third experiment that we report has the objective of showing how the bandwidth of the spurious term, f_c, can be reduced. For this purpose the experimental arrangement includes an optical source with larger bandwidth, 28 nm, and a dispersive element that shows higher dispersion, a fiber of 46-km length. We implemented a four-tap negative filter by using two lasers and two 1-cm-long UFBGs, with maximum reflectivity of 16 dB. The second term of Eq. (2) does not appear in Fig. 6 because f_c is less than 0.130 GHz (minimum frequency of the LCA). The FSR is 0.815 GHz, and the 3-dB bandwidth of the filter is 0.176 GHz, with a wavelength separation between taps of 1.56 nm, according to a fiber with a linear dispersion of 17 ps/(nm × km) at 1550 nm. Therefore, for larger frequencies than f_c, the filter exhibits perfect agreement between the experimental results (solid curves) and the theoretical response of an ideal four-tap filter with two negative coefficients.

In summary, we have demonstrated a novel approach to setting up transversal filters with positive and negative taps. Our approach facilitates the flexible design of transfer functions by using a laser array and a broadband optical source filtered by UFBGs. Unlike previous configurations, our simple method is based on all-optical and passive elements and exhibits higher tunability and lower cost than previously reported systems. The spurious term that our filters generate is limited to a low-frequency bandwidth and can be electrically filtered in the system's receiver.

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