

All-optical microwave bandpass filter with negative coefficients based on a phase modulator and linearly chirped fiber Bragg gratings

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A novel all-optical microwave bandpass filter with negative coefficients is presented. Positive and negative coefficients are obtained through conversion from phase modulation to intensity modulation by passing the phase-modulated optical carriers through chirped fiber Bragg gratings having group-delay responses with positive and negative slopes. A two-tap transversal microwave filter with one negative coefficient is experimentally implemented. © 2005 Optical Society of America

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The all-optical microwave filters proposed in the past few years are mostly based on incoherent manipulation of optical carriers with only positive taps, and only low-pass filtering functionality can be realized. For many applications, such as radio-over-fiber systems, bandpass or flat-top filters are required. To overcome this limitation, several techniques^{1–7} have been proposed in the past few years. Recently, we reported a method for implementing an all-optical microwave bandpass filter with a simple structure,⁸ in which the baseband resonance of a typical low-pass filter is eliminated by using an electro-optic phase modulator (EOPM) combined with a dispersive device. In the proposed approach, the effective transfer function $H(\omega)$ is the multiplication of two frequency responses, i.e., a conventional low-pass frequency response $H_2(\omega)$ and a dispersion-induced phase-modulation-to-intensity-modulation (PM-IM) conversion $H_1(\omega)$. $H_1(\omega)$ has a notch at the dc frequency. Consequently, by carefully choosing the system parameters to let the second resonance peak of $H_2(\omega)$ locate exactly at the same position of the first peak of $H_1(\omega)$, one can ensure a frequency response equivalent to that of a bandpass filter. It is different from the negative coefficient bandpass filters proposed in Refs. 2–7; however, no negative taps are actually generated in this approach. Therefore, bandpass filtering with a flat-top passband and a larger mainlobe-to-sidelobe ratio (MSR) is not possible with this approach.

In this Letter, we propose a novel method for realizing an all-optical microwave bandpass filter with negative coefficients. Positive and negative coefficients are obtained through PM-IM conversion by reflecting the phase-modulated optical carriers from linearly chirped fiber Bragg gratings (LCFBGs) with positive or negative dispersions. The fundamental concept is shown in Fig. 1. Under small signal modulation conditions, the phase-modulated optical spectrum is illustrated on the left side of Fig. 1, which consists of an optical carrier (ω_0) and two first-order sidebands ($\omega_0 - \omega_m, \omega_0 + \omega_m$, where ω_m represents the modulating microwave frequency). At the output of

the EOPM, the two sidebands are π out of phase. It is different from an IM where the two sidebands at the output of an intensity modulator are in phase. If the phase-modulated signal is directly detected with a photodetector (PD), the modulating signal cannot be recovered, and only a dc signal is observed because beating between the carrier and the upper sideband exactly cancels the beating between the carrier and the lower sideband. However, as shown in Fig. 1, if the modulated optical signal passes through a dispersive device, the phase relationship between any two optical frequency components will change due to the chromatic dispersion. When this dispersed optical signal is fed to a PD, the modulating signal can be recovered, which implies that the PM is converted to IM by the dispersive device.

More interestingly, when $D = \partial\tau/\partial\omega > 0$ (the upper case in Fig. 1), the higher optical frequency component experiences more phase shift than that of the lower frequency component, and eventually the PM-IM conversion is fully achieved when all three frequency components are exactly in phase. To the contrary, when $D = \partial\tau/\partial\omega < 0$ (the lower case in Fig. 1), the lower frequency component will experience more phase shift than the higher one, and the PM-IM con-

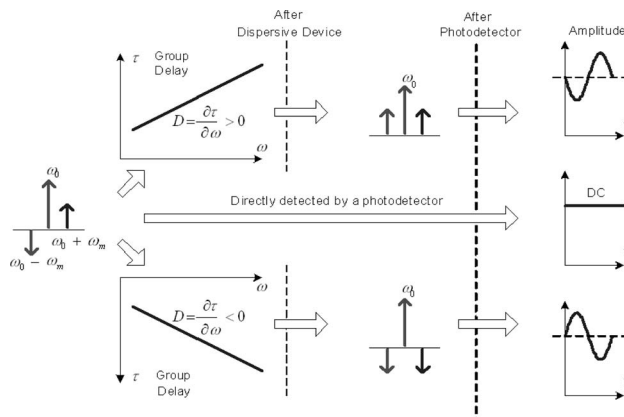


Fig. 1. Illustration of the recovered rf modulating signals that sustain a positive, zero, or negative chromatic dispersion.

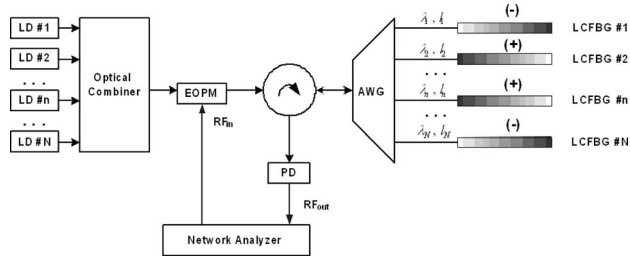


Fig. 2. System configuration of the proposed all-optical microwave bandpass filter with negative coefficients.

version is fully obtained when the two sidebands have the same phase but are π out of phase with the carrier. Consequently, the recovered rf signals from the different dispersive devices will have a π phase inversion, which can be directly applied to implement negative coefficients in an all-optical microwave filter.

Mathematically, the recovered microwave signal from such a PM-IM conversion followed by a direct detection can be expressed by Eq. (1), which shows that the amplitude of the recovered rf signal, denoted as $E_{rf}(t)$, is a function of the system-induced dispersion as well as the modulating frequency,⁸

$$E_{rf}(t) \propto \sin\left(\frac{1}{2}D\omega_m^2\right) \cos(\omega_m t + \varphi), \quad (1)$$

where D is the chromatic dispersion of the dispersive device and φ is the phase delay of the recovered microwave signal, which is also determined by D and ω_m . Based on Eq. (1), some important conclusions can be drawn to help us build a multitap microwave bandpass filter with negative coefficients. First, both positive and negative coefficients can be obtained by letting the phase-modulated optical carriers experience chromatic dispersions with different signs since $\sin(D\omega_m^2/2)$ is obviously an odd function. LCFBGs are a good candidate to be used as the dispersive devices since LCFBGs can provide linear group-delay (GD) profiles. The GD slope of a LCFBG can be easily reversed by connecting the optical input to the opposite port of the grating. Second, the PM-IM conversion efficiency reaches the maxima when $\sin(D\omega_m^2/2) = \pm 1$, which implies that the free spectral range (FSR) of the proposed filter should be carefully designed to match the PM-IM conversion maxima; then an optimized filtering output can be obtained.

Based on the theoretical analysis, a basic architecture for the proposed filter is presented in Fig. 2. Optical carriers from an array of N laser diodes (LDs) emitting at $\lambda_1, \lambda_2, \dots, \lambda_n, \dots, \lambda_N$ are combined via an optical combiner and applied to an EOPM. Through an optical circulator, the modulated optical signals are demultiplexed by an arrayed-waveguide grating (AWG) and fed to N LCFBGs via either the short-wavelength or the long-wavelength port, depending on whether the LCFBGs are employed to implement positive or negative taps. The reflected and dispersed optical signals are then multiplexed by the same AWG and sent to a PD to recover the modulating rf

signal. The recovered rf signal can be expressed as a vector summation of the resulting electrical signals from the N carriers, and the frequency response of the proposed all-optical microwave filter is then written as

$$H(\omega) \propto \sum_{n=1}^N P_n \sin\left(\frac{1}{2}D_n\omega_m^2\right) \exp[j\omega_m(n-1)\Delta\tau], \quad (2)$$

where P_n and D_n represent the optical power of the n th LD and the dispersion of the n th LCFBG, respectively. Basically, P_n determines the weight of the n th tap, and the sign of D_n determines whether this tap is positive or negative. The length difference between any two adjacent optical paths ($l_{n+1} - l_n = \Delta l, n = 1, 2, \dots, N-1$) determines the central frequency of the passband, i.e., $\text{FSR} = 1/\Delta\tau = c/2n_{\text{eff}}\Delta l$, where c is the optical wave propagation velocity in free space and n_{eff} is the effective refractive index.

Although a multichannel optical coupler can be used to replace the AWG, the use of an AWG can reduce the system insertion loss and at the same time eliminate the intertap interference. The LCFBGs are required to have different central wavelengths corresponding to those of the LD array. The lengths and chirp rates of the LCFBGs should be identical to ensure that the dispersions of the LCFBGs are identical in magnitude. The small implementation error of the delay line length of the fiber link between the AWG and each LCFBG can be accurately compensated by slightly tuning the corresponding LD wavelength to be reflected at different positions in the LCFBG.

To prove the concept, a two-tap microwave filter with one negative coefficient is implemented. Two LCFBGs are fabricated through one linearly chirped phase mask. By applying different tension to the fiber during the UV exposure process, a central wavelength shift of 0.7 nm is achieved. A Gaussian apodization profile is applied to flatten and smooth the reflectivity response and the group delay ripples. Both gratings have a length of 8 cm. The measured GD and reflectivity responses for both gratings, one is measured at the short-wavelength port (denoted as LCFBG#1), and the other is measured at the long-wavelength port (denoted as LCFBG#2), are shown in Fig. 3, from which the average dispersions of LCFBG#1 and LCFBG#2 are calculated to be 1350 and -1327 ps/nm, respectively.

Two tunable LDs emitting at λ_1 and λ_2 with identical output power levels and a typical linewidth of 150 kHz are applied as the light sources. Since no

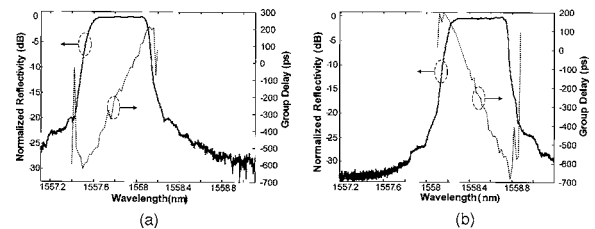


Fig. 3. Measured reflectivity and GD responses of (a) LCFBG#1 and (b) LCFBG#2.

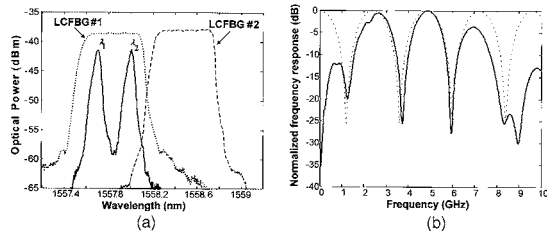


Fig. 4. Experimental results of the implemented filter with two positive taps. (a) Measured optical spectrum (solid curve) before the PD when both LDs are reflected from the same port of LCFBG#1. (b) Frequency responses: measured (solid curve) and simulated $H_2(\omega)$ (dotted curve) showing low-pass filtering.

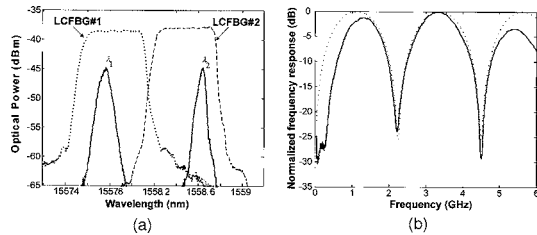


Fig. 5. Experimental results of the two-tap filter with one negative coefficient. (a) Measured optical spectrum (solid curve) when λ_1 is reflected by LCFBG#1 from the short-wavelength port and λ_2 is reflected by LCFBG#2 from the long-wavelength port. (b) Frequency responses: measured $H(\omega)$ (solid curve) and simulated $H_2(\omega)$ (dotted curve), showing a bandpass filtering with one negative tap.

AWG is available at the time of the experiment, a 3 dB coupler is used to replace the AWG. First, the wavelengths of the two LDs are tuned to be reflected by LCFBG#1 via the same port, as shown in Fig. 4(a), in which these two phase-modulated optical signals are reflected from different positions of LCFBG#1, but the dispersions experienced are identical thanks to the linearity of the GD profile. The frequency response of the filter observed from the network analyzer is shown in Fig. 4(b). The measured FSR is about 2.4 GHz, corresponding to a time interval of 417 ps. Comparing the measured frequency response with the simulated low-pass response $H_2(\omega)$, it is clearly seen that the baseband resonance of the low-pass filter is eliminated due to the PM-IM conversion. This situation is the same as our approach demonstrated in Ref. 8, which can be considered as an equivalent bandpass filter with all positive coefficients.

However, keeping λ_1 fixed, λ_2 is tuned to be reflected by LCFBG#2, as shown in Fig. 5(a), which has

a reversed GD slope with respect to that of LCFBG#1. The measured frequency response of the filter is shown in Fig. 5(b). In this case, the FSR is 2.25 GHz, corresponding to a time interval of 444 ps. It is observed from Fig. 5(b) that $H_2(\omega)$ has a transfer function corresponding to a bandpass filter and a negative coefficient is indeed obtained. By comparing the frequency responses in Figs. 4(b) and 5(b), we can see that the low-pass resonance of the bandpass-equivalent filter is only partially suppressed by the dc notch generated by the PM-IM conversion, a relatively high sidelobe at the low frequency is observed. For the frequency response in Fig. 5(b), since it is a true bandpass filter with a negative tap, no low-pass resonance exists in the frequency response; a frequency response with a higher MSR (15 dB improvement) is obtained.

In conclusion, a novel approach to implementing an all-optical microwave bandpass filter with negative coefficients has been proposed and demonstrated. The proposed filter has a simple structure with positive or negative coefficients obtained through PM-IM conversion by reflecting the phase-modulated optical carriers from the regular LCFBGs with positive or negative GD slopes. A two-tap microwave bandpass filter with one negative tap was demonstrated, it has a better MSR compared to the bandpass-equivalent filter with all-positive taps. More taps with either positive or negative weights can be easily realized by simply adding more LCFBGs, which provides the possibility of implementing microwave bandpass filters with a flat-top response and a high MSR.

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References

1. S. Sales, J. Capmany, J. Marti, and D. Pastor, *Electron. Lett.* **31**, 1095 (1995).
2. F. Coppinger, S. Yegnanarayanan, P. D. Trinh, and B. Jalali, *IEEE Trans. Microwave Theory Tech.* **45**, 1473 (1997).
3. X. Wang and K. T. Chan, *Electron. Lett.* **36**, 2001 (2000).
4. S. Li, K. S. Chiang, W. A. Gambling, Y. Liu, L. Zhang, and I. Bennion, *IEEE Photon. Technol. Lett.* **12**, 1207 (2000).
5. J. Capmany, D. Pastor, A. Martinez, B. Ortega, and S. Sales, *Opt. Lett.* **28**, 1415 (2003).
6. E. H. W. Chan and R. A. Minasian, *IEEE Photon. Technol. Lett.* **16**, 1370 (2004).
7. J. Mora, M. V. Andres, J. L. Cruz, B. Ortega, J. Capmany, D. Pastor, and S. Sales, *Opt. Lett.* **28**, 1308 (2003).
8. F. Zeng and J. P. Yao, *Opt. Express* **12**, 3814 (2004).