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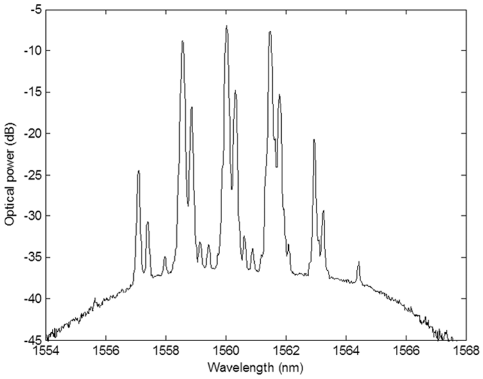

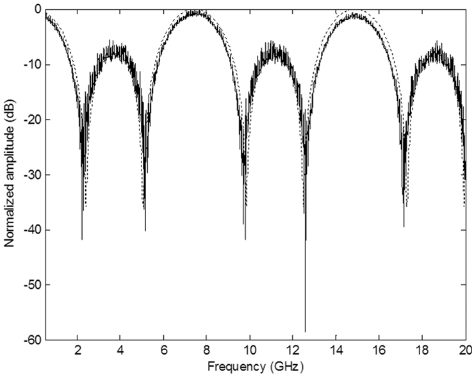

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Reconfigurable Photonic Microwave Filter Based on Four-Wave Mixing

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Abstract: A simple technique to reshape the response of tapped delay line photonic microwave filters is demonstrated. The technique is based on the generation and control of a set of optical carriers by means of four-wave mixing. Experimental results show reconfiguration from 2 to 5 taps with uniform and apodized amplitude distributions.

Index Terms: Photonic microwave filter, microwave photonics signal processing, four-wave mixing.

1. Introduction

Photonic technology offers an alternative implementation of microwave filtering which shows attractive features over its pure electric counterparts: wide bandwidth (up to 100 GHz), seamless tunability, low sensitivity to electromagnetic interference, and potential of integration with radio over fiber links [1], [2]. In the last years different approaches have been proposed including infinite-impulse response filters [3], ring resonators [4], [5], nonlinear effects in fiber [6] and finite-impulse response tapped delay line filters [7]–[12].

Among these options, delay line filters have attracted particular interest due to their flexibility to implement a wide range of functionalities such as flat-top bandpass responses based on positive and negative coefficients, fast tuning, etc. On the other side, this approach is traditionally based on using as many optical sources as filter taps which limits its scalability. To overcome this limitation, reduce cost and ease practical deployment, several methods have been studied. These include the use of optical spectrum slicing [7], which reduces the filter performance in terms of noise; and comb sources [10]–[12], which offer good performance but can require complex control signaling, increasing the complexity of the system. In [12] fast tuning as well as high stopband attenuation (70 dB) were demonstrated using comb sources combined with four-wave mixing (FWM) with the double objective of increasing the number of modes and smoothing the comb response. The former approach however does not offer, in principle, the control of the individual laser mode amplitudes and thus have restricted capabilities to dynamically control the filter response by means of tap windowing. Some schemes have addressed this issue by offering limited control or an increase in complexity [13], [14].

In this paper, an approach to increase the number of taps featuring dynamically control the filter shape based on FWM is demonstrated. By controlling the gain of an optical amplifier and the state of polarization the number of taps of the filter as well as its response shape can be controlled.

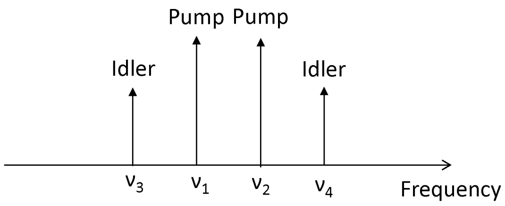

Fig. 1. Schematic spectrum of frequency components generated for partially degenerated FWM.

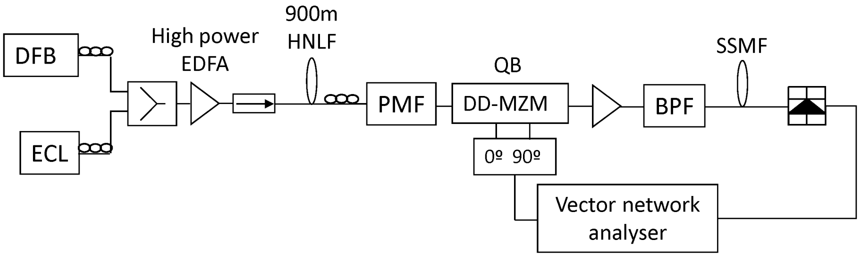

Fig. 2. Experimental setup of the reconfigurable multiple tap delay line filter based on two optical carriers. PMF: Polarization maintaining fiber, BPF: bandpass filter.

2. Principle of Operation

The technique is based on the dynamic control of the shape and number of optical carriers (i.e., filter taps) in a taped delay line FIR filter based on a set of optical carriers and a dispersive medium by means of FWM. FWM is a parametric process given by the third-order electric susceptibility of the fiber [15]. In general it occurs when three waves of different wavelength (ν_1, ν_2, ν_3) copropagate in a fiber generating new waves whose frequencies are a combination of the original frequencies. If all the degenerate and partially degenerate processes are taken into account products at nine new frequencies are produced although the weaker frequencies are usually neglected and only the strongest frequency component at $\nu_4 = \nu_3 + (\nu_2 - \nu_1) = \nu_2 + (\nu_3 - \nu_1)$, known as idler, is considered. In the particular case where only two waves of different frequency are present, case known as partially degenerated FWM, two idler waves are generated as shown in Fig. 1 although by increasing the power of the optical carriers it is possible to generate additional carriers. Thus, by controlling the power of the pump carriers (for instance using an optical amplifier) it is possible to control the number of carriers (filter taps) and their amplitude. Additionally, further control may be obtained by adding optical filtering after the FWM carrier generation stage to improve the control of the filter amplitude distribution.

FWM generated idler carriers can be used to increase the number of taps of a photonic microwave filter while keeping control of the relative amplitude among the carriers, i.e., controlling the shape of the filter response.

The technique does not affect the tuning of the filter response, which may be performed either by changing the wavelength spacing between the original optical carriers or changing total dispersion in the dispersive medium, as reported elsewhere [1].

3. Experimental Results

The experimental setup is shown in Fig. 2. Two continuous-wave optical sources (one distributed feedback laser, DFB, at 1559.6 nm and one external cavity laser, ECL at 1560.4 nm) were used as pump waves. These are amplified by a high-power erbium-doped fiber amplifier (EDFA) and applied to a reel of highly nonlinear fiber (HNLF). The HNLF used has a zero dispersion wavelength (λ_0) of 1562 nm, a dispersion slope S of 0.018 $\text{ps}/(\text{nm}^2 \cdot \text{km})$, a nonlinear coefficient γ

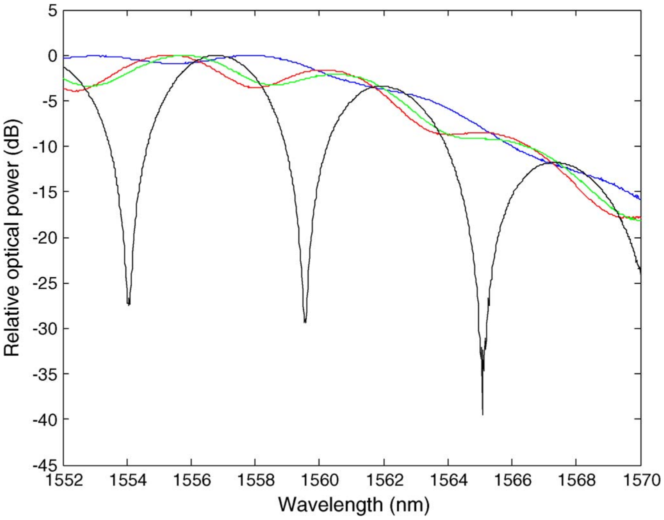

Fig. 3. (a) Some optical filter response implemented with a PMF and an external amplitude modulator for different input polarization states.

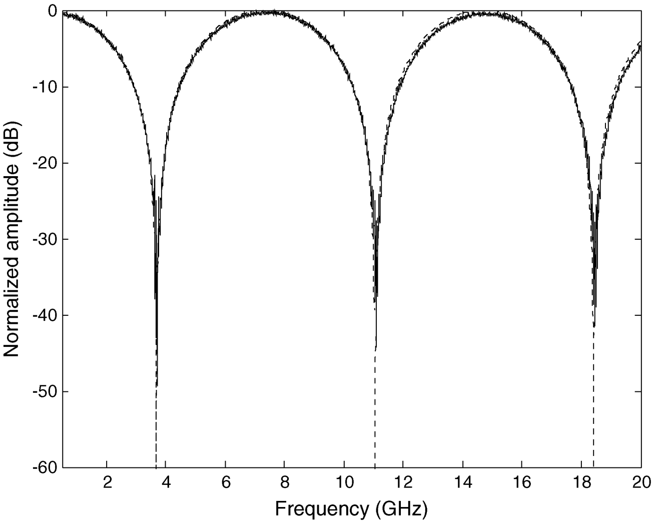

Fig. 4. Notch filter response obtained with low EDFA gain. The solid curve represents experimental results and dashed one theoretical results obtained from fitted parameters.

of 10.8 $W^{-1} \cdot km^{-1}$ and a length of 900 meters. At the output of the fiber FWM results in the generation of new carriers.

The filter response is controlled by changing the number and relative amplitude of the optical carriers. It is done by changing the power of the pump carriers through the gain of the optical amplifier. Additionally, to increase control over the optical carriers, the amplitudes of the optical carriers can be adjusted by means of optical filtering [16]–[19]. A polarization controller and a short length of polarization maintaining fiber (differential group delay, DGD, of around 1.5 ps), is introduced after the HNLF. It results in an optical filter generated by the light travelling along the two axes of the modulator with the DGD introduced by the PMF. Fig. 3 shows the optical filter response obtained for different polarization states at the input of the PMF. As it can be seen the optical filter FSR is around 5.5 nm which agrees with the theoretical value (5.4 nm). This optical filtering stage allows further adjustment

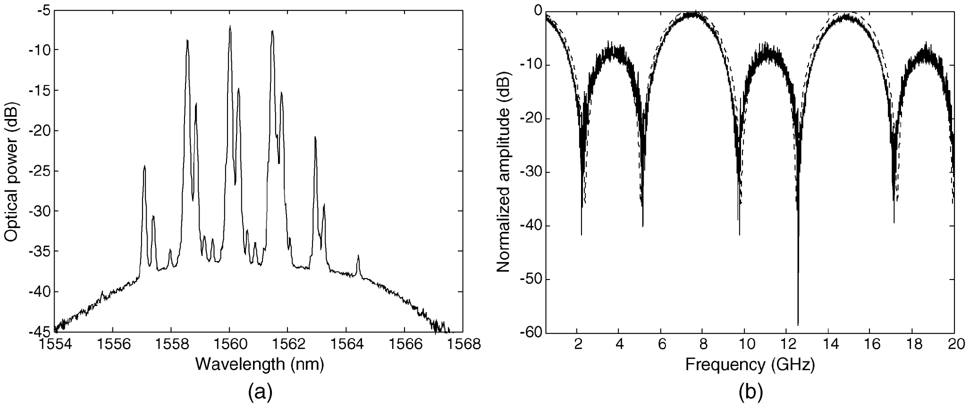

Fig. 5. (a) Optical spectrum; (b) Three-tap filter response. Solid curve experimental results, dashed curve theoretical results obtained from fitted parameters.

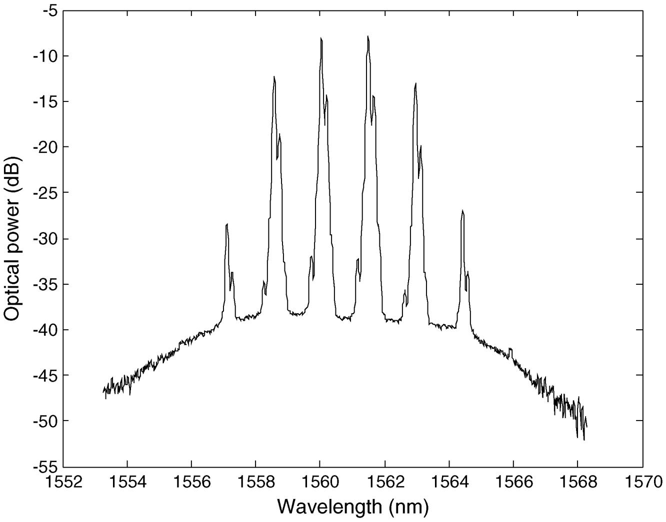

Fig. 6. Optical carriers corresponding to a four-tap amplitude distribution according to a Hanning window.

of the amplitudes of the set of optical carriers. After the filter control stage, optical carriers are modulated in a quadrature-biased (QB) Mach–Zehnder modulator, fed by the microwave signal generated by a vector network analyzer (Agilent PNA-X). To avoid dispersion induced fading a dual-drive MZM is used to get single sideband modulation (SSB). After modulation the signals are amplified and filtered to reduce noise and launched to a reel of 10 km standard single mode fiber (SSMF) where time delays are generated through fiber dispersion. Finally, the signals are photodetected and the filter response obtained as the S_{21} parameter in the vector network analyzer.

Controlling the gain of the high-power EDFA and the polarization at the input of the PMF it is possible to control the amplitude distribution of the optical powers and therefore reshape the filter response. Fig. 4 shows the filter response using the setup of Fig. 2 when the high-power EDFA is kept at low gain, no significant FWM is generated and a two-tap notch filter response is obtained as in a conventional tapped delay line photonic microwave filter.

If the gain of the high-power EDFA is increased, idler carriers are generated [Fig. 5(a)]. To shape the filter response the gain of the EDFA is adjusted jointly with the optical filter response generated by the combination of PMF birefringence and the polarization axis of the external modulator.

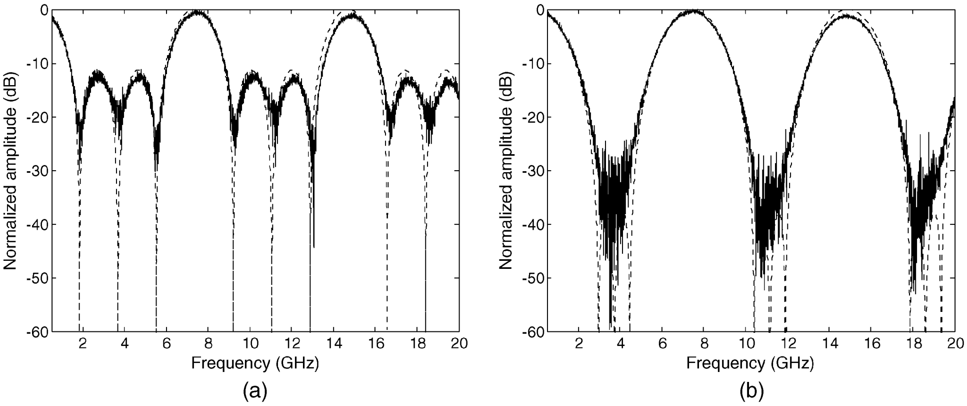

Fig. 7. Four-tap filter response. (a) Uniform amplitude distribution; (b) Hanning window distribution as shown in Fig. 5. Solid curves represent experimental results, and dashed curves theoretical results obtained from fitted parameters.

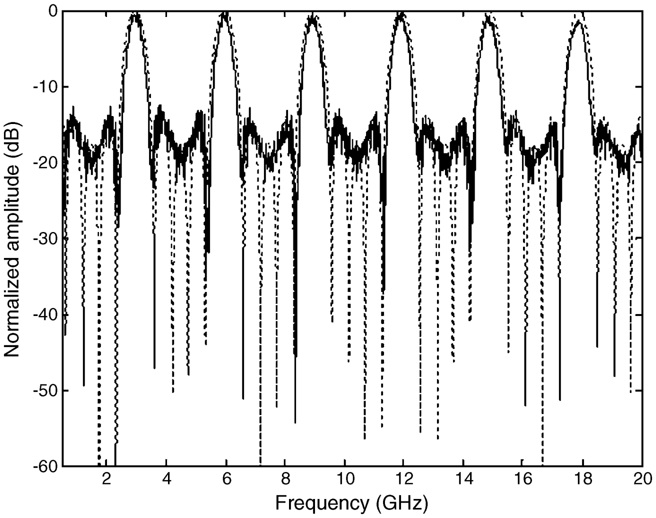

Fig. 8. Five-tap filter response. Solid curve experimental results, dashed curve theoretical results obtained from fitted parameters.

Adjusting both EDFA gain and polarization at the input of the PMF, a three-tap delay line filter can be implemented as shown in Fig. 5(a) where the optical spectrum showing SSB-modulated optical carriers is depicted. Fig. 5(a) shows how several idler waves are generated but only some of them, three in this case, have enough power to generate significant microwave taps. As it can be seen in Fig. 5(b), a uniform amplitude distribution can be obtained.

Fig. 6 shows results for a four-tap delay line filter. Both uniform and particular amplitude distributions (for instance, a Hanning window) can be obtained with the proposed technique as shown in Figs. 6 and 7(b).

Finally, a five-tap apodized filter response ([0.8 1 1 1 0.8]) is obtained as shown in Fig. 8. In this case a dispersive fiber of 25 km was used and the filter used to reduce noise was eliminated to accommodate the FWM-generated optical carriers.

Although the proposed technique has been demonstrated for a modest number of seeding optical carriers the principle can be expanded to generate a number N of spectral samples starting from N/2 pumping laser modes.

4. Conclusion

An approach to dynamically reshape the transfer function of a multitap photonic microwave filter by changing the number of taps and controlling the amplitude distribution has been demonstrated. Proof-of-concept experiments have shown the dynamic reconfiguration of a photonic microwave filter response by changing both the number of taps from 2 to 5 in a setup with two optical sources and the amplitude window (uniform and Hanning). The scheme is simple and can be easily integrated in radio over fiber links.

References

[1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nat. Photon.*, vol. 1, no. 6, pp. 319–330, Jun. 2007.

[2] J. Yao, "Microwave Photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, 2009.

[3] E. H. W. Chan and R. A. Minasian, "Coherence-free photonic notch filter," *Electron. Lett.*, vol. 40, no. 21, pp. 1375–1377, Oct. 2004.

[4] M. S. Rasras, K. Y. Tu, D. M. Gill, Y. K. Chen, A. E. White, S. S. Patel, A. Pomerene, D. Carothers, J. Beattie, M. Beals, J. Michel, and L. C. Kimerling, "Demonstration of a tunable microwave-photonic notch filter using low-loss silicon ring resonator," *J. Lightw. Technol.*, vol. 27, no. 12, pp. 2105–2110, Jun. 15, 2009.

[5] J. Palací, G. E. Villanueva, J.V. Galán, J. Martí, and B. Vidal, "Single bandpass photonic microwave filter based on a notch ring resonator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 17, pp. 1276–1278, Sep. 2010.

[6] B. Vidal, M. A. Piqueras, and J. Martí, "Tunable and reconfigurable photonic microwave filter based on stimulated Brillouin scattering," *Opt. Lett.*, vol. 32, no. 1, pp. 23–25, Jan. 1, 2007.

[7] A. P. Foord, P. A. Davies, and P. A. Greenhalgh, "Synthesis of microwave and millimetre-wave filters using optical spectrum-slicing," *Electron. Lett.*, vol. 32, no. 4, pp. 390–391, Feb. 1996.

[8] J. Capmany, D. Pastor, and B. Ortega, "New and flexible fiber-optic delay line filters using chirped fiber Bragg gratings and laser arrays," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1321–1326, Jul. 1999.

[9] B. Vidal, J. L. Corral, and J. Martí, "All-optical WDM multi-tap microwave filter with flat bandpass," *Opt. Exp.*, vol. 14, no. 2, pp. 581–586, Jan. 23, 2006.

[10] M. Bolea, J. Mora, B. Ortega, and J. Capmany, "Highly chirped single-bandpass microwave photonic filter with reconfiguration capabilities," *Opt. Exp.*, vol. 19, no. 5, pp. 4566–4576, Feb. 28, 2011.

[11] M. Song, C. M. Long, R. Wu, D. Seo, D. E. Leaird, and A. M. Weiner, "Reconfigurable and tunable flat-top microwave photonic filters utilizing optical frequency combs," *IEEE Photon. Technol. Lett.*, vol. 23, no. 21, pp. 1618–1620, Nov. 2011.

[12] V. R. Supradeepa, C. M. Long, R. Wu, F. Ferdous, E. Hamidi, D. E. Leaird, and A. M. Weiner, "Comb-based radiofrequency photonic filters with rapid tunability and high selectivity," *Nat. Photon.*, vol. 6, no. 3, pp. 186–194, Feb. 2012.

[13] B. Vidal, M. A. Piqueras, and J. Martí, "Photonic microwave filter based on spectrum slicing with reconfiguration capability," *Electron. Lett.*, vol. 41, no. 23, pp. 1286–1287, Nov. 10, 2005.

[14] J. Capmany, J. Mora, D. Pastor, and B. Ortega, "High-quality online-reconfigurable microwave photonic transversal filter with positive and negative coefficients," *Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2730–2732, Dec. 2005.

[15] G. P. Agrawal, *Nonlinear Fiber Optics,* 3rd ed., San Diego, CA: Academic, 2001.

[16] B. Vidal, T. Mengual, C. Ibáñez-López, and J. Martí, "WDM photonic microwave filter with variable cosine windowing based on a DGD module," *Photon. Technol. Lett.*, vol. 18, no. 21, pp. 2272–2274, Nov. 2006.

[17] Q. Wang and J. Yao, "Multitap photonic microwave filters with arbitrary positive and negative coefficients using a polarization modulator and an optical polarizer," *Photon. Technol. Lett.*, vol. 20, no. 2, pp. 78–80, Jan. 2008.

[18] H. Y. Jiang, L. S. Yan, J. Ye, W. Pan, B. Luo, and X. S. Yao, "Comb filter with independently tunable wavelength spacing and bandwidth using cascaded variable differential group delay elements," *Opt. Lett.*, vol. 36, no. 12, pp. 2305–2307, Jun. 2011.

[19] L. S. Yan, J. Ye, H. Y. Jiang, W. Pan, B. Luo, A. L. Yi, Y. H. Guo, and X. S. Yao, "A photonic comb filter with independently and digitally tunable bandwidth and frequency spacing," *IEEE Photon. Technol. Lett.*, vol. 23, no. 13, pp. 857–859, Jul. 2011.