WDM Photonic Microwave Filter with Variable Cosine Windowing based on a DGD Module

Borja Vidal, *IEEE Member*, Teresa Mengual, Cristina Ibáñez-López, Javier Martí, *IEEE Member*

***Abstract*— A simple method for windowing the response of WDM photonic microwave transversal filters based on one DGD module is proposed. The technique allows the reconfiguration of photonic microwave filters based on cost-effective sources such as spectrum-slicing of broadband sources or multiwavelength lasers. Proof-of-concept experimental results are provided.**

***Index Terms*— Microwave photonics, photonic microwave filters, apodization.**

I. INTRODUCTION

Photonic filtering of microwave and millimetre-wave signals provide advantages such as large time-bandwidth products, low weight, immunity to electromagnetic interference and, especially, tuning and reconfiguration capabilities not shown by traditional microwave filter implementations as well as the potential to be integrated in a fiber link (reusing most of its components) [1-10]. Among the different filtering schemes, photonic finite impulse response filters based on a set of optical carriers (WDM) and a dispersive medium provide a large level of flexibility and, therefore, several filter functionalities have been demonstrated [3-10]. To implement good-quality filter responses a large number of optical carriers (i.e. filter taps) are needed. Since the use of a set of independent lasers is expensive due to the unavailability of low-cost integrated laser arrays, the use of multiwavelength lasers or spectrum slicing of broadband sources [3] was proposed to implement low-cost filters. Although using this approach the filter responses can be tuned (by changing total dispersion), the capability of changing the shape of the filter response (reconfiguration) by windowing the optical carriers is more complicated. Several approaches to ease this issue have been proposed using large AWGs and attenuators [8], filters and attenuators [9] and spatial light modulators and diffraction gratings [10]. These techniques require several components and can be bulky when scaled to a large number of optical carriers. It would be interesting to achieve the reconfiguration capability with a single low-loss device, especially if it can be used independently of the number of filter taps. However, it presents a trade-off between using a single device and the loss of individual tap weighting (i.e. full arbitrary reconfiguration).

Manuscript received May 20, 2006. B. Vidal, T. Mengual, C. Ibáñez–López and J. Martí are with the Nanophotonics Technology Center, Universidad Politécnica de Valencia, Camino de Vera, s/n, Valencia, Spain (Tel:+34963879747, Fax: +34963877827, email: bvidal@ieee.org).

In this Letter, a simple technique based on a DGD module to change the amplitude of a set of optical carriers (i.e. to reconfigure the filter response shape) is demonstrated.

II. PRINCIPLE OF OPERATION

The technique is based on introducing a birefringent medium before the Mach-Zehnder Modulator (MZM), for instance, a DGD module [11], to change the relative amplitude between a set of optical carriers of equal amplitude. Birefringence introduces a change on the state of polarization of the optical carriers. If the incoming set of carriers is launched at 45º to the DGD axis, the phase shift between orthogonal polarization components of light depends on optical frequency as given by,

$$\phi = 2\pi f DGD \tag{1}$$

where f is optical frequency and DGD is the differential group delay. Since MZMs are polarization dependent, optical carriers suffer different attenuations depending on its state of polarization which can be controlled by the DGD and the wavelength spacing between optical carriers. The windowing response experienced by each optical carrier is,

$$amplitude = \cos(2\pi f DGD + \varphi) \tag{2}$$

where the term φ represents the dependence of the windowing response on the axis of the MZM. It means that a set of optical carriers will have different polarizations at the output of a birefringent medium. Depending on the frequency spacing between optical carriers, the DGD range has to be adjusted to obtain the desired attenuation.

Equation (2) shows that it is possible to control the relative amplitude of a set of optical carriers, according to the cosine relation shown in (2). It allows the windowing of the filter taps using multiple optical carriers and a dispersive medium.

Figures 1 and 2 show how, given a certain number of optical carriers and their wavelength spacing, a different amplitude window can be implemented changing the DGD value and, therefore, the filter response can be reconfigured. Figure 1(a) depicts the amplitude for seven optical carriers with a wavelength spacing of 0.4 nm (marked with asterisks) and the windowing generated by (2) with a DGD value of 0.1 ps. Figure 1(b) shows the filter response obtained assuming a 10-km coil of standard single mode fiber, SSMF, with D=17 ps/(nm·km). Figure 2 shows the windowing produced by a DGD of 0.8 ps (a) and the filter response (b) with the same assumptions made in Figure 1.

The frequency period between notches given by (2) depends on the DGD value. Therefore, since the set of optical carriers is fixed, the polarization at the input of the MZM has to be changed to center the window response obtained with the pair DGD-MZM with the central carrier of the optical source. It can be done using a polarization controller.

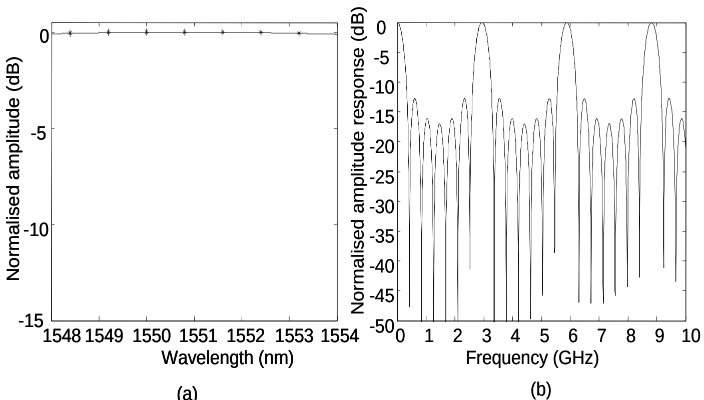

Fig. 1.- (a) Amplitude of the optical carriers (asterisks) and window generated with DGD=0.1 ps (solid line); (b) Filter response for seven carriers with amplitudes shown in (a) assuming a dispersive medium made by 10-km SSMF of D=17 ps/(nm·km).

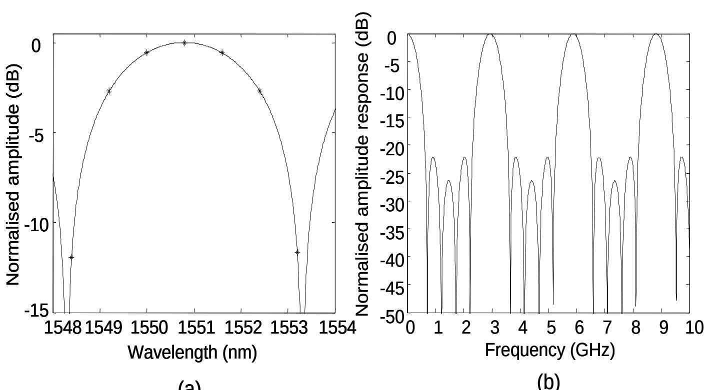

Fig. 2.- (a) Amplitude of the optical carriers (asterisks) and window generated with DGD=0.8 ps (solid line); (b) Filter response for seven carriers with amplitudes shown in (a) assuming a dispersive medium made by 10-km SSMF of D=17 ps/(nm·km).

Figure 3 shows the block diagram of a filter based on this technique. After the multiwavelength laser (MWL), a DGD module is used to introduce birefringence. Commercial DGD modules developed for PMD emulation provide variable DGD values, allowing the dynamic reconfiguration of the filter response. Once the set of optical carriers has been apodised, a dispersive medium is used to introduce a time delay, as usual in this kind of photonic microwave filters. Then, the signals are photodetected.

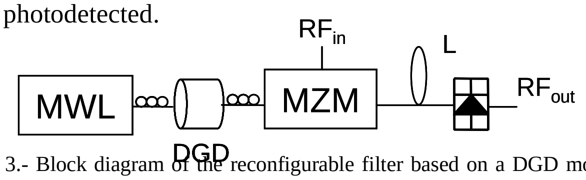

Fig. 3.- Block diagram of the reconfigurable filter based on a DGD module. MWL: multiwavelength laser.

This apodization technique can be used both with optical sources made with multiwavelength lasers or the spectrum slicing of broadband sources [3] and can also be combined with architectures intended to allow the tuning of the filter response (e.g. [12]).

III. Experimental Setup

To validate the concept, the setup of Figure 4 was used. The multiwavelength source was implemented using three independent lasers, a coupler and three polarization controllers. A polarization analyser was used to ensure that the three independent lasers have the same state of polarization at the output of the coupler (as would happen in a real multiwavelength laser). Then, the signal is launched to the DGD module which provides a variable amount of birefringence. Since the DGD values where relatively large, the wavelength spacing between optical carriers has to be small and therefore a wavelength spacing of 0.4 nm was used ([1549.4 1549.8 1550.2] nm). After the DGD a polarization controller is used to adjust the state of polarization at the input of the MZM (it has to be done for each value of the DGD). A Dual-Drive Mach-Zehnder Modulator (DD-MZM) was used as modulator to generate a single sideband (SSB) and avoid the carrier suppression degradation of dispersive fiber although it is not necessary for the proposed technique. Then an Erbium Doped fiber amplifier (EDFA) was used to compensate for the loss of the fiber. As dispersive medium a coil of 25 km of SSMF was used. Then, the signal was split to the photodiode and an optical spectrum analyser to monitor the apodization of the optical carriers achieved with the DGD. The filter response was obtained using a vector network analyser.

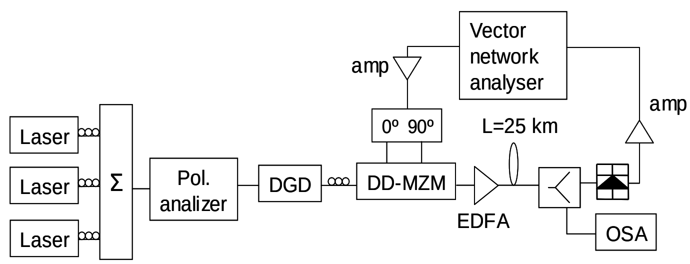

Fig. 4.- Experimental setup using three optical carriers and a coil of 25-km of SSMF as dispersive medium. OSA: Optical Spectrum Analyser.

Figures 5 and 6 show the amplitude distribution of the optical carriers and the filter response for two values of the DGD, 2.1 and 3.42 ps, respectively. Figure 5 shows how a uniform distribution can be implemented and how the proper filter response is obtained. On the other side, Figure 6 shows how for larger DGD values, the lateral carriers are attenuated, i.e. the taps of the transversal filter are apodized, reducing the amplitude of the sidelobes of the filter response. A slight variation in the amplitude of the optical carriers is due to changes in the EDFA gain when the power of the optical carriers is changed by the DGD. Figures 5b and 6b show a good agreement with the expected theoretical values. A 4 dB amplitude variation can be seen in the figures and it is due to the amplifier response. It has been taken into account on the theoretical numerical simulations.

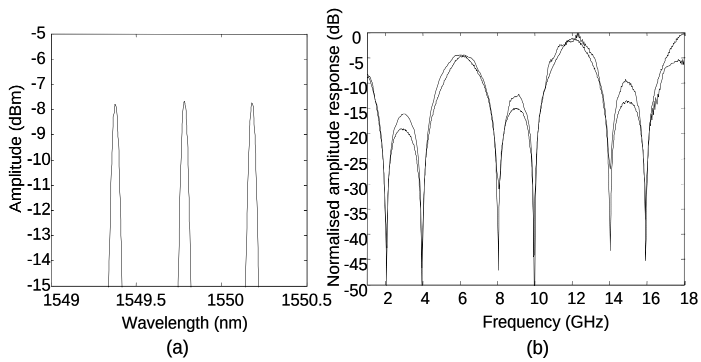

Figure 5.- (a) Amplitude of the three optical carriers with DGD=2.1 ps as shown in the OSA; (b) Measured filter response for three taps with amplitudes shown in (a). The solid curve corresponds with measurements and the dashed one with theory.

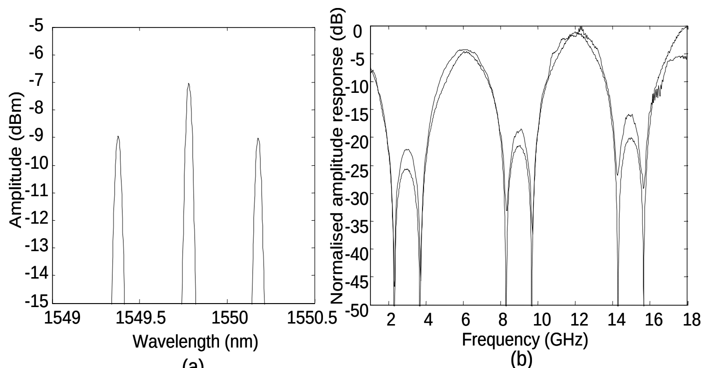

Figure 6.- (a) Amplitude of the three optical carriers with DGD=3.42 ps as shown in the OSA; (b) Measured filter response for three taps with amplitudes shown in (a). The solid curve corresponds with measurements and the dashed one with theory.

Finally, Figure 7 show several filter responses for different values of the DGD to compare the different filter responses obtained. These measurements show that using a DGD module the filter transfer function can be reconfigured. In particular, the nominal values of DGD have been [2.1 3.42 4.99 6.35] ps.

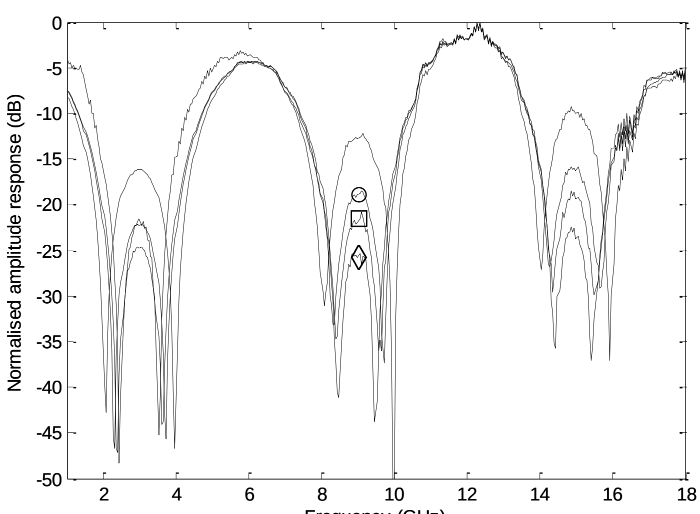

Figure 7.- Comparison of the filter response reconfiguration capability for different values of DGD: solid (2.1 ps), solid-circle (3.42 ps), solid-square (4.99 ps) and solid-diamond (6.35 ps).

IV. CONCLUSION

In this Letter, a technique to reshape the response of photonic microwave filters based on a set of optical carriers and dispersive media has been proposed. The architecture is based on using a DGD module and a polarization analyzer and is independent of the number of optical carriers to be apodized. In addition, the technique can be used in optical beamforming applications if the apodisation is implemented optically. Finally, experimental results to validate the concept have been provided

ACKNOWLEDGMENT

This work has been partially funded by the Spanish MCyT under the project TEC2005-08298-C02-02 and the European Space Agency though OBEFONE project.

REFERENCES

[1] B. Moslehi, J.W. Goodman, M. Tur, H.J. Shaw, "Fiber-optic lattice signal processing", Proc. IEEE, vol. 72, no. 7, pp. 909-930, July 1984.
[2] D.B. Hunter, R.A. Minasian, "Photonic signal processing of microwave signals using an active-fiber Bragg-grating pair structure", IEEE Trans. Microw. Theory Tech., vol. 45, no. 8, pp.1463-1466, August 1997.
[3] A.P. Foord, P.A. Davies and P.A. Greenhalgh, "Synthesis of microwave and millimetre-wave filters using optical spectrum-slicing", IEE Electronics Letters, vol. 32, no. 4, pp. 390-391, 1996.
[4] F. Zheng, J. Wang, J. Yao, "All-optical microwave bandpass filter with negative coefficients based on a phase modulator and linearly chirped fiber Bragg gratings", Optics Letters, vol. 30, no. 17, pp. 2203-2205, September 2005.
[5] B. Vidal, V. Polo, J. L. Corral, J. Martí, "Harmonic suppressed photonic microwave filter", *Journal of Lightwave Technology*, vol. 21, no. 12, December 2003.
[6] B. Vidal, V. Polo, J. L. Corral, J. Martí, "Efficient architecture for WDM photonic microwave filters", IEEE Photonics Technology Letters, vol. 16, no. 1, pp. 257-259, January 2004.
[7] B. Vidal, J. L. Corral, J. Martí, "All-Optical WDM Microwave Filter with Negative Coefficients", IEEE Photonics Technology Letters, vol. 17, no. 3, pp. 666-669, March 2005.
[8] D. Pastor, B. Ortega, S. Sales, A. Martínez, P. Muñoz, "Optical microwave filter based on spectrum slicing by use of arrayed waveguide gratings", Optics Letters, vol. 28, no. 19, pp. 1802-1804, 2003.
[9] B. Vidal, M. A. Piqueras, J. Martí, "Photonic microwave filter based on spectrum slicing with reconfiguration capability", IEE Electronics Letters, vol. 41, no. 23, pp. 1286-1287, 10 November 2005.
[10] J. Capmany, J. Mora, D. Pastor, B. Ortega, "High-Quality Online Reconfigurable Microwave Transversal Filter with Positive and Negative Coefficients", IEEE Photonics Technology Letters, vol. 17, no. 12, pp. 2730-2732, December 2005.
[11] L.S. Yan, C. Yeh, G. Yang, L. Lin, Z. Chen, Y.Q. Shi, X. Steve Yao, "Fast Digitally Variable Differential Group Delay Module using Polarization Switching", Optical Fiber Conference (OFC), Postdeadline Paper FA5-1, Anaheim (USA), March 17-22, 2002.
[12] B. Vidal, V. Polo, J. L. Corral, J. Martí, "Photonic microwave filter with tuning and reconfiguration capabilities using optical switches and dispersive media", *IEE Electronics Letters*, vol. 39, no. 6, pp. 547-549, 20th March 2003.