Harmonic Suppressed Photonic Microwave Filter

B. Vidal, *Student Member, IEEE*, V. Polo, *Student Member, IEEE*, J. L. Corral, *Member, IEEE*, and J. Martí, *Member, IEEE*

***Abstract*—This paper proposes a photonic microwave filter based on wavelength-division multiplexing (WDM) of multiple optical carriers and dispersive media. Harmonic suppression is obtained using nonuniform tap spacing to extend the filter free spectral range by a Vernier effect. The experimental results presented are in excellent agreement with theory.**

***Index Terms*—Microwave photonics, nonuniform tap spacing, photonic microwave filters, Vernier effect, wavelength-division multiplexing (WDM).**

I. Introduction

MICROWAVE photonics makes feasible the efficient distribution of microwave/millimeter-wave signals for advanced broad-band access networks as well as for processing such signals directly in the optical domain. Photonic filters allow processing of radio frequency (RF) signals after optical modulation, avoiding costly intermediate optoelectronic conversions. Optical processing presents many advantages, such as low and RF-independent loss, small size, immunity to electromagnetic interference, as well as large time-bandwidth products that are especially interesting at higher modulating frequencies where wide-band electrical processing is more difficult [1]. Different architectures have been proposed using a variety of fiber-optic devices such as highly dispersive fibers [2], fiber Bragg gratings (FBGs) [3], [4], fiber-optic prisms [5], arrayed- waveguide gratings (AWGs) [6], [7], or optical switches [8]. Among them, architectures based on commercial optical devices, multiple optical carriers (exploiting wavelength-division multiplexing (WDM), and dispersive media are especially well suited to reduce the cost of photonic microwave filters.

Photonic microwave transversal filters present periodic power transfer functions with their passbands (harmonics) equally spaced. The spectral range between two successive passbands of the filter is called free spectral range (FSR), which is a constant in conventional filters having uniform tap spacing. The FSR depends on the time delay ($\Delta\tau$) between the filter taps ($\mathrm{FSR} = 1/\Delta\tau$). To increase the filter operation bandwidth and, moreover, to reduce harmonics produced by nonlinear devices such as amplifiers or mixers, these unwanted periodic passbands should be eliminated.

Manuscript received April 21, 2003; revised July 3,2003. This was supported in part by the European Commission under Project IST 2000-25390 (OBANET) and by the Spanish Ministry of Science and Technology under Grant TIC2000-2793-CE. The authors acknowledge the Spanish Research and Technology Commission (CICYT) for funding the project TIC2000-1674.

The authors are with the Fiber-Radio Group (FRG), Universidad Politécnica de Valencia, 46022 Valencia, Spain (e-mail: bvidal@ieee.org).

Digital Object Identifier 10.1109/JLT.2003.822255

In this paper, we present, as far as we know, the first photonic microwave filter with harmonic suppression to increase the filter rejection bandwidth. Harmonic suppression is obtained by wavelength multiplexing of several optical carriers with a nonuniform spacing and using a dispersive medium to extend the filter FSR by a Vernier effect.

A. Principle of Operation

The proposed architecture is based on a set of optical carriers and a dispersive medium, as shown in Fig. 1, to obtain a set of time-delayed electrical taps and, therefore, a transversal filter. The dispersive medium can be standard single-mode fiber (SSMF), highly dispersive fiber, or chirped FBGs. Unlike previous proposals, in the proposed architecture, there is not a constant time delay between taps, i.e., a nonuniform wavelength spacing between optical carriers has been employed. Removing this constraint and using an appropriate nonuniform spacing distribution, the spectral filter transfer function becomes the product of two uniform-tap-spaced transversal filters (basic filters), according to the Vernier effect (Fig. 2). By properly choosing the frequency shift between the two basic filters, a nonconstant FSR can be obtained, increasing the filter rejection bandwidth.

To derive the time delay between taps, the product of two filter responses is calculated as follows:

$$|H_T(f)| = |H_A(f)| \cdot |H_B(f)| \tag{1}$$

where $H_A(f)$ and $H_B(f)$ are the RF filter responses of the filters with uniform tap spacing.

The filter amplitude transfer function for an equally spaced N-tap transversal filter using a conventional optical amplitude modulation and assuming an optimum polarization adjustment is given by [3]

$$|H_{\mathrm{RF}}(f)| = \cos\left(\frac{\beta f^2}{2}\right)\left|\sum_{k=1}^{N} P_k e^{-j[2\pi f(k-1)\Delta\tau]}\right| \tag{2}$$

where f is the electrical frequency, β is the dispersion parameter, P_k is the optical power of source k, and $\Delta\tau$ is the time delay between optical carriers due to the dispersive media. The first term in (2) is the well-known dispersion-induced carrier suppression effect due to propagation of the RF signal through the dispersive medium, which degrades the filter operation. This effect can be compensated by employing single-sideband (SSB) modulation at the Mach–Zehnder modulator (MZM) [9]. In this case, the filter amplitude response is

$$|H_{\mathrm{RF}}(f)| = \left|\sum_{k=1}^{N} P_k e^{-j[2\pi f(k-1)\Delta\tau]}\right|. \tag{3}$$

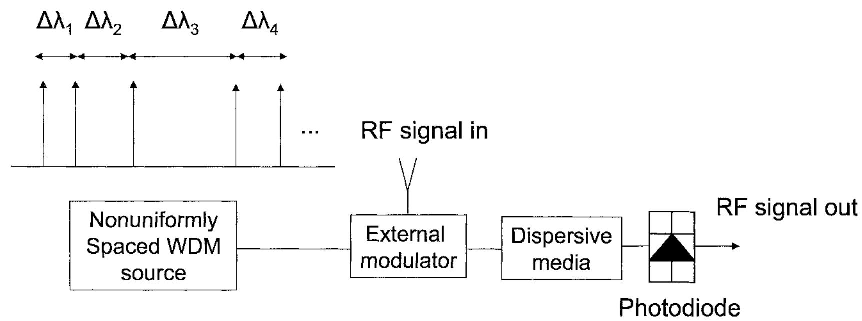

Fig. 1. Schematic diagram for the harmonic suppressed photonic microwave filter based on nonuniform tap spacing.

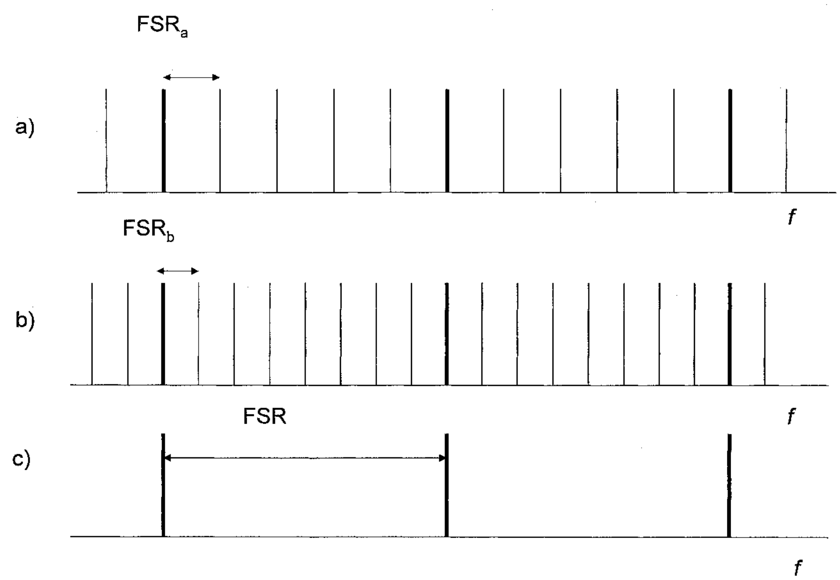

Fig. 2. Vernier principle: (a) spectral response of filter a; (b) spectral response of filter b; and (c) composed spectral filter response according to Vernier principle.

Combining the filter response of two filters with different time delays, the total transfer function is obtained

$$|H_T(f)| = \left(\sum_{i=1}^{N} P_i e^{-j[2\pi f(i-1)\Delta\tau_{\mathrm{a}}]}\right) \cdot \left(\sum_{k=1}^{M} P_k e^{-j[2\pi f(k-1)\Delta\tau_{\mathrm{b}}]}\right) \quad (4)$$

where N and M are the number of taps of the two basic filters.

After manipulation, it can be obtained that the absolute time delay distribution of the filter taps is

$$[\mathrm{i}\Delta\tau_{\mathrm{a}} + \mathrm{k}\Delta\tau_{\mathrm{b}}], \quad \text{with } \mathrm{i} = 0 \cdots N-1, \mathrm{k} = 0 \cdots M-1 \quad (5)$$

so that the number of taps in the nonuniformly spaced filter is equal to $N \cdot M$. For instance, assuming two uniformly spaced filters of three taps (each $M = N = 3$), the absolute time delay distribution of the filter taps yields

$$[0, \Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{b}}, 2\Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{a}} + \Delta\tau_{\mathrm{b}}, 2\Delta\tau_{\mathrm{b}}, 2\Delta\tau_{\mathrm{a}} + \Delta\tau_{\mathrm{b}}, \Delta\tau_{\mathrm{a}} + 2\Delta\tau_{\mathrm{b}}, 2\Delta\tau_{\mathrm{a}} + 2\Delta\tau_{\mathrm{b}}]. \quad (6)$$

From (6), the relative time delay between adjacent taps can be obtained as

$$[\Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, 2\Delta\tau_{\mathrm{a}} - \Delta\tau_{\mathrm{b}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, 2\Delta\tau_{\mathrm{a}} - \Delta\tau_{\mathrm{b}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{a}}]. \quad (7)$$

The relative time delay between optical carriers in dispersive media is given by

$$\Delta\tau = \mathrm{D_T} \cdot \Delta\lambda \quad (8)$$

where $\mathrm{D_T}$ corresponds to the total dispersion (in picoseconds per nanometer), and $\Delta\lambda$ is the wavelength spacing (in nanometers) between optical carriers. From (7), it can be seen that a nonuniform spacing between optical carriers results in nonuniform time delays between taps.

The synthesis of photonic microwave filters with harmonic suppression involves several steps. Once the central frequency for the desired filter passband is fixed, the time delay ($\Delta\tau_{\mathrm{a}}$ and $\Delta\tau_{\mathrm{a}}$) between taps for the two uniformly spaced filters are calculated. In a second step, to increase the filter rejection bandwidth, a frequency shift (Δf) has to be added between the two basic filter responses. Due to the cumulative effect of this frequency shift, the spectral response repetitions spaced multiples

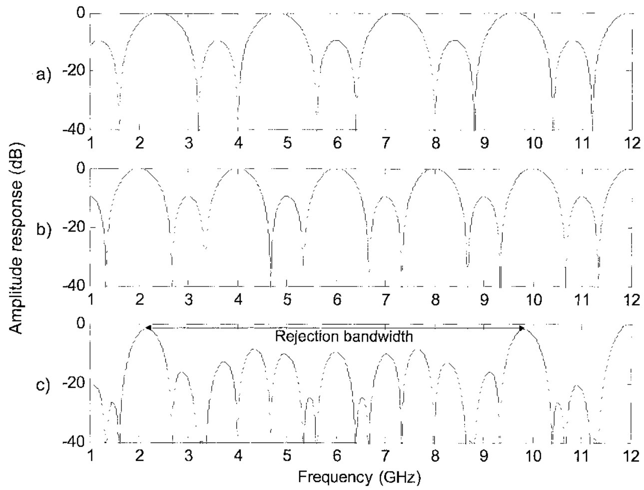

Fig. 3. Spectral filter response simulations which show the rejection bandwidth increase using Vernier principle: (a) spectral response for filter (a) with constant wavelength spacing ($\Delta\tau_{\rm a} = 499.1$ ps); (b) spectral response for filter b) with constant wavelength spacing ($\Delta\tau_{\rm b} = 416.6$ ps); and (c) spectral filter response with increased rejection bandwidth obtained using nonuniform tap spacing.

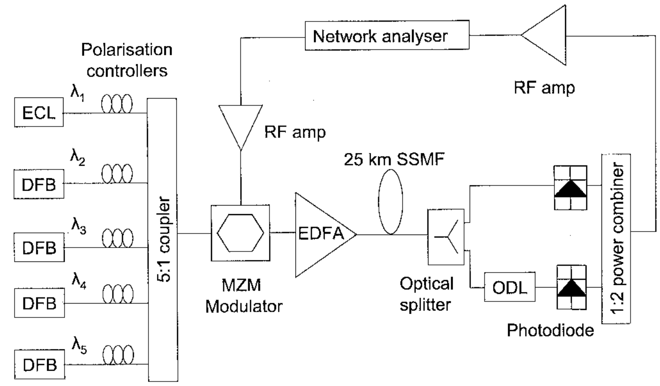

Fig. 4. Experimental setup for a ten-taps harmonic-suppressed photonic microwave filter using an ODL and a second photodiode to increase the number of filter taps by reusing the optical carriers.

of FSRs from the first passband do not exactly match, being eliminated from the nonuniform-tap-spaced filter response and therefore increasing the rejection bandwidth.

As an example, Fig. 3 shows spectral response simulations obtained using the nonuniform tap spacing given by (7), assuming the same amplitude for all filter taps (rectangular window), 25 km of SSMF with $\mathrm{D} = 16.5$ ps$/(\mathrm{nm} \cdot \mathrm{km})$ as dispersive medium and $\Delta\lambda_{\rm a} = 1.21$ nm (i.e., $\Delta\tau_{\rm a} = 499.1$ ps) and $\Delta\lambda_{\rm b} = 1.01$ nm (i.e., $\Delta\tau_{\rm b} = 416.6$ ps). Fig. 3(a) and (b) depicts the spectral response for both basic three-tap filters ($\Delta\lambda_{\rm a} = 1.21$ nm and $\Delta\lambda_{\rm b} = 1.01$ nm, respectively), and Fig. 3(c) shows the spectral response of the nonuniformly spaced tap filter using (7). It can be seen from Fig. 3 that the product of the two basic responses is obtained.

The rejection bandwidth can be estimated as

$$\mathrm{BW}_{\rm rejection} = (\xi - 1) \cdot \mathrm{FSR} + \xi \cdot \Delta f \tag{9}$$

where ξ is the number of FSR multiples needed for equaling the cumulative frequency shift to FSR

$$\xi = \frac{\left(\mathrm{FSR} - \frac{\mathrm{BW}}{2}\right)}{\Delta \mathrm{f}} \tag{10}$$

where BW is the filter -1 dB bandwidth, and Δf is the frequency shift between the filter responses of both basic filters. In the simulation results of Fig. 3, the rejection bandwidth is 7.66 GHz. The rejection bandwidth estimation of (9) is 7.6 GHz. At first approach, Δf should be equal to the maximum $\mathrm{BW}_{-1\ \rm dB}$ of both basic filter responses (since they present different FSRs, their $\mathrm{BW}_{-1\ \rm dB}$ are slightly different). This frequency shift has to be iteratively optimized to maximize the mainlobe-to-sidelobe level, since there are many degrees of freedom in the design of the filter.

Both the secondary sidelobe level and the rejection bandwidth depend on the number of taps and the spectral shift between basic filter responses. Therefore, they can be improved by increasing the number of taps. Moreover, the secondary sidelobe level can be increased by windowing the time samples of the impulse response with an appropriate window as known from digital filter design theory [10], i.e., weighting the power level of optical carriers.

This technique to increase the rejection bandwidth does not require specific devices and therefore can be directly implemented in photonic microwave filter architectures based on tunable laser arrays [3]. On the other hand, although a larger number of optical taps than conventional uniformly spaced filters are needed with this technique, this problem can be partially solved by using efficient techniques to increase the number of taps in WDM-based filters [11].

Tuning of the nonuniformly spaced tap filter response can be implemented by changing the total dispersion $(\mathrm{D_T})$ of the dispersive medium [8] or, in filter architectures based on tunable optical sources [3], by recalculating the wavelength spacing between taps.

II. Experimental Results

To demonstrate the feasibility of the proposed architecture, experimental results are provided. The experimental setup is depicted in Fig. 4. The WDM nonuniform source has been implemented using four narrow-tuning distributed feedback (DFB) lasers and one wide-tuning external-cavity laser (ECL), whose output signals were combined using a standard fiber-optic coupler. The specific wavelengths of the optical carriers were $\lambda_1 = 1550.77$ nm, $\lambda_2 = 1550.47$ nm, $\lambda_3 = 1549.72$ nm, $\lambda_4 = 1549.52$ nm, and $\lambda_5 = 1548.53$ nm. A dual-drive MZM was employed as the external modulator. To avoid the carrier suppression effect, SSB modulation was used instead of amplitude modulation, as stated in Section II. An erbium-doped fiber amplifier (EDFA) was used to compensate for optical losses. A 25-km SSMF coil with $\mathrm{D} = 16.5$ ps$/(\mathrm{nm} \cdot \mathrm{km})$ was used as the dispersive medium, which corresponds to the product of two basic filters of $\mathrm{FSR_a} = 2.5$ GHz and $\mathrm{FSR_b} = 2$ GHz. Two RF amplifiers were used to boost the RF signal from/to a vector network analyzer used to measure the filter response. In order

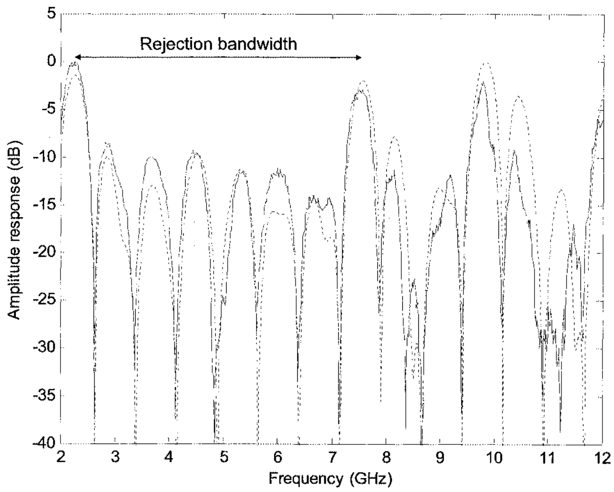

Fig. 5. Measured nonuniform-tap-spaced filter spectral response. Solid line corresponds to experimental results, and dotted line corresponds to simulation.

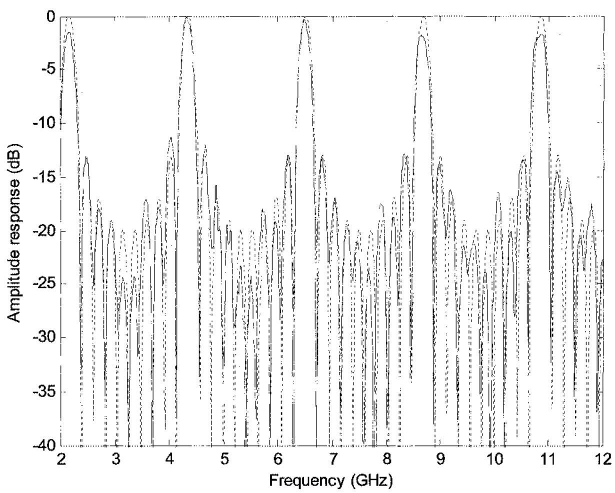

Fig. 6. Measured uniform-tap-spaced filter spectral response. Solid line corresponds to experimental results, and dotted line corresponds to simulation.

to increase the number of taps, the technique described in [11] has been used. According to this technique, a second photodiode has been introduced to the architecture scheme to obtain ten taps using only five optical sources. An optical delay line (ODL) between the two photodiodes allows the reuse of the optical carriers, and therefore, the number of taps is increased. The absolute propagation time delay is selected slightly higher than the total dispersion-induced time delay introduced by the five optical taps, and therefore, ten optical taps (instead of nine) can be obtained. In this way, the experimental time delay distribution is not the one shown in (7) but a rearranged one with an extra tap, as given by

$$[\Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, 2\Delta\tau_{\mathrm{a}} - \Delta\tau_{\mathrm{b}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{a}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}, 2\Delta\tau_{\mathrm{a}} - \Delta\tau_{\mathrm{b}}, \Delta\tau_{\mathrm{b}} - \Delta\tau_{\mathrm{a}}]. \quad (11)$$

The measured spectral response of the harmonic-suppressed filter over the range of 2–12 GHz obtained with the time-delay distribution of (11) is depicted in Fig. 5. The electrical bandwidth is limited by the available power combiner used to add signals coming from both photodiodes. However, practical wide-band power combiners to higher frequencies are commercially available. The spectral response shown in Fig. 5 has a rejection bandwidth of around 5 GHz with a mainlobe at 2 GHz in contrast to previously reported uniformly spaced tap photonic transversal filters showing constant FSR. Fig. 5 shows that the mainlobe-to-sidelobe level has been slightly reduced as compared with conventional uniformly spaced tap filter. Fig. 6 depicts the experimental spectral filter response of a uniform-tap-spaced filter of ten taps that has also been implemented by using the technique proposed in [11]. Figs. 5 and 6 show that the rejection bandwidth can be increased from 2 GHz of uniformly spaced tap filters to 5 GHz using nonuniform tap spacing.

III. Conclusion

A new photonic microwave filter with harmonic suppression based on nonuniform tap spacing has been proposed. Experimental results confirming the feasibility of the proposed scheme have been presented, showing an excellent agreement with theory. This new functionality can be directly implemented in several photonic microwave filter architectures, increasing the flexibility of photonic microwave filters based on WDM signals and dispersive media.

References

[1] K. P. Jackson, S. A. Newton, B. Moleshi, M. Tur, C. C. Cutler, J. W. Goddman, and H. J. Shaw, "Optical fiber delay-line signal processing," *IEEE Trans. Microwave Theory Tech.*, vol. 33, pp. 193–209, Mar. 1985.

[2] D. Norton, S. Johns, C. Keefer, and R. Soref, "Tunable microwave filter using high dispersion fiber time delays," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 831–832, July 1994.

[3] 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. Microwave Theory Tech.*, vol. 47, pp. 1321–1326, July 1999.

[4] R. A. Minasian and D. B. Hunter, "Photonic signal processing of microwave signals using fiber Bragg gratings," in *Proc. Optical Fiber Conf.*, 1997, ThH3, pp. 339–340.

[5] M. Y. Frankel and R. D. Esman, "Fiber optic tunable microwave transversal filter," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 191–193, Feb. 1995.

[6] F. Coppinger, S. Yegnanarayanan, P. D. Trinh, and B. Jalali, "Continuously tunable photonic radio-frequency notch filter," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 339–341, Mar. 1997.

[7] V. Polo, B. Vidal, J. L. Corral, and J. Martí, "Novel tunable photonic microwave filter based on laser arrays and $N \times N$ AWG-based delay lines," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 584–586, Apr. 2003.

[8] B. Vidal, V. Polo, J. L. Corral, and J. Martí, "Photonic microwave filter with tuning and reconfiguration capabilities using optical switches and dispersive media," *Electron. Lett.*, vol. 39, no. 6, pp. 547–549, Mar. 2003.

[9] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fiber-radio systems," *Electron. Lett.*, vol. 33, no. 1, pp. 74–75, Jan. 1997.

[10] A. Oppenheim and R. Schaffer, *Discrete Time Signal Processing*. Englewood Cliffs, NJ: Prentice-Hall, 1989.

[11] B. Vidal, V. Polo, J. L. Corral, and J. Martí, "Cost-effective photonic microwave filter employing tap reusing," in *Proc. 2003 Int. Topical Meeting Microwave Photonics (MWP 2003)*, Budapest, Hungary, Sept. 10–13, 2003, pp. 267–270.

B. Vidal (S'99) was born in Alicante, Spain, on April 24, 1978. He received the Ingeniero de Telecomunicación degree from the Polytechnic University of Valencia, Valencia, Spain, in 2001 and is currently working toward the Ph.D. degree at the same university.

He is a Member of the Fiber-Radio Group of the Nanophotonics Technology Center, Polytechnic University of Valencia. His research interests include phased-array antennas, optical beam-forming networks, photonic microwave filters, and microwave and millimeter-wave optical fiber systems.

V. Polo (S'93) received the Ingeniero de Telecomunicación and Dr. Ingeniero de Telecomunicación (Ph.D.) degrees from the Universidad Politécnica de Valencia, Spain, in 1997 and 2003, respectively.

He is a Member of the Fiber-Radio Group of the Valencia Nano-photonics Technology Center (CTnF), Universidad Politécnica de Valencia, where he is involved at research and management levels in national and European research and development projects dealing with microwave photonics. His research interests in this field include external modulators, photonic-microwave filters, dispersion compensation, and broad-band wireline and wireless access technologies and systems. He has coauthored more than 60 papers in international journals and conferences and is a reviewer for several journals and conferences.

J. L. Corral (S'90–A'98–M'01) was born in Zaragoza, Spain, on April 20, 1969. He received the Ingeniero de Telecomunicación degree (first-class honors) and the Dr. Ingeniero de Telecomunicación (Ph.D.) degree from the Universidad Politécnica de Valencia, Valencia, Spain, in 1993 and 1998, respectively.

During 1993, he was Assistant Lecturer at the Departamento de Comunicaciones at the Universidad Politécnica de Valencia. From 1993 to 1995, he was at the Microwave Technology & Equipment Section (XRM) at the European Space Research & Technology Centre (ESTEC, The Netherlands) from the European Space Agency (ESA), where he was engaged in research on MMIC-based technologies and photonics technologies for beam-forming networks for on-board phased-array antennas. In 1995, he joined the Communications Department at the Universidad Politécnica de Valencia, where he became an Associate Professor in 2000. His research interests include phased-array antennas, optical beam-forming networks, digital beam forming, and microwave and millimeter-wave optical fiber systems. He has authored or coauthored more than 40 papers in international journal and conference proceedings in his areas of research interest.

Dr. Corral is a Member of several societies of IEEE. He was recipient of the 1998 Doctorate Prize of the Telecommunications Engineer Association in Spain for his Ph.D. dissertation on applications of MMIC and photonic technologies to phased-array antennas.

J. Martí (S'89–M'92) received the Ingeniero de Telecomunicación degree from the Universidad Politécnica de Catalunya, Catalunya, Spain, in 1991 and the Dr. Ingeniero de Telecomunicación (Ph.D.) degree from the Universidad Politécnica de Valencia, Valencia, Spain, in 1994.

From 1989 to 1990, he was an Assistant Lecturer at the Escuela Universitaria de Vilanova, Barcelona, Spain. From 1991 to 2000, he was a Lecturer and an Associate Professor at the Telecommunication Engineering Faculty, the Universidad Politécnica de Valencia, where he is currently Professor and leads the Radio over Fiber Group. He has authored or coauthored more than 100 papers in refereed international technical journals and more than 50 papers in international conference proceedings in the fields of microwave/millimeter-wave photonics, wavelength-division-multiplexing (WDM) optical networks, optical processing, and planar photonic crystals.

Prof. Martí has served as a Member of the Technical Program Committee of the ECOC and several other international workshops and conferences.