Photonic Tunable Microwave Transversal Filter based on Optical Switches and Fiber Dispersion

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Abstract — **A tunable and reconfigurable photonic microwave filter based on a switched dispersion matrix (SDM) is proposed. The SDM consists of n 2x2 optical switches and a dispersive medium between them. The architecture shows discrete filter tuning and reconfiguration capabilities using an array of fixed lasers which reduce the system cost regarding other proposals based on broadband tunable lasers. Tuning capabilities have been experimentally demonstrated.**

I. Introduction

The use of photonic microwave filters has been proposed to overcome the electronic bottleneck in communication systems with high dynamic range, high compactness, high bandwidth and fast reconfiguration and tuning requirements as, for instance, for RADAR applications [1-6]. Photonic microwave filters benefit also from the low loss and size of optical fiber devices and cables as well as from immunity to electro-magnetic interference (EMI). A number of photonic microwave transversal filters have been proposed using fiber-optic devices as highly dispersive fibers [1], fiber-optic prisms [2], fiber Bragg gratings [3-5] or arrayed waveguide gratings (AWG) [6]. Some schemes [1]-[4] exploit wavelength division multiplexing to simplify the architecture by using as many wide band tunable sources as taps the filter has. It can be a potentially good solution for notch filters, where only two tunable sources are needed, but becomes impractical to synthesize RF filters with many taps.

In this paper, a photonic WDM microwave filter based on a multiwavelength laser (MWL) and a switched dispersion matrix (SDM) is proposed. Optical switches and dispersive media have been previously proposed for optical antenna beamforming applications [7]. This scheme allows discrete tuning and has reconfiguration capabilities using multiwavelength sources, laser arrays or low cost spectrum sliced sources. All of them drastically reduce the system overall cost over previous proposals using wide-range tunable laser arrays.

II. Filter Description

The configuration of the proposed transversal filter is depicted in Figs. 1 and 2.

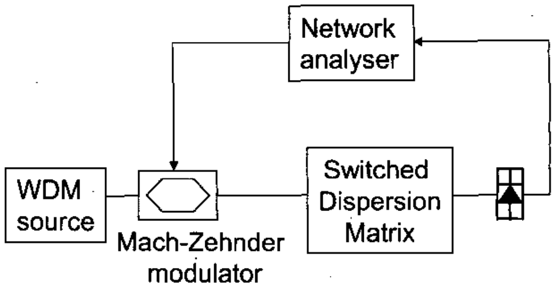

Fig. 1.- Switched photonic microwave filter.

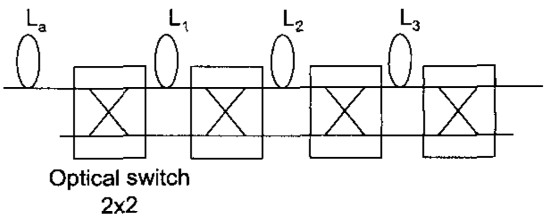

Fig. 2.- Switched dispersion matrix (SDM).

The WDM source can be implemented using one MWL [8], an array of fixed lasers or the spectrum slices of a broadband source [9]-[10]. All the optical carriers are simultaneously amplitude modulated by the RF/microwave electrical signal using an external modulator. The signals experience differential delay due to wavelength dependence delay of the dispersive elements. The SDM is implemented with n 2x2 optical switches and some dispersive medium between them as well as a first dispersive element which determines the maximum filter free spectral range (FSR_{filter}). These dispersive elements can be for instance, standard single mode fibers (SSMF), highly dispersive fibre or chirped fibre gratings.

In the SDM, the dispersive elements introduce an exponentially increasing dispersion, i.e. [D_0, $2D_0$, 2^2D_0,..., $2^{n-1}D_0$], in order to define a binary delay line. Other optical delay lines have been studied [11] but binary delay lines reduce the number of switches and dispersive elements required. The total dispersion of the optical delay line depends on the switch configuration and is given by,

$$D_T = D_a + \sum_{i=1}^{n} 2^{i-1} D_0 S_i \qquad (1)$$

where D_a is the dispersion introduced by the first dispersive element (in Fig. 1, L_a), n is the number of bits of the SDM (i.e. the number of dispersive elements), D_0 is the basic dispersion increment and S_i is the state of switch i (0 or 1). The total dispersion of the SDM vary from D_a to $D_a+2^{n-1}\cdot D_0$ in increments of D_0 ps/nm.

From (1), the microwave filter response obtained is given by,

$$H(f_{RF}) \alpha \cos\left(\beta f_{RF}^2\right) \sum_n E_n^2 e^{j2n\upsilon \beta f_{RF}} \qquad (2)$$

where f_{RF} is the frequency of the input signal, f_0 is the carrier optical frequency, E_n^2 is optical power of the n-th optical carrier, υ is the optical frequency separation between the optical carriers. $\beta = \pi c D_T / f_0^2$ is the propagation constant, c being the speed of light in the vacuum and D_T (ps/nm) being the total first order dispersion given by Eq. 1.

The FSR_{filter} depends on the time delay introduced by the dispersive media which is selected by the optical switches. If the dispersive elements are implemented using fiber paths, the photonic microwave filter FSR is,

$$FSR_{filter} = \frac{1}{D_T \cdot \Delta\lambda} = \frac{1}{D \cdot (L_a + L_i) \Delta\lambda} \qquad (3)$$

where D_T is the fibre dispersion parameter, $\Delta\lambda$ is the wavelength spacing between optical carriers, L_a is the first fibre length and L_i is the fibre length selected by the optical switches. L_a determines the FSR_{filter} whereas the set of optical switches changes the total fibre length, implementing a discrete tuning.

The filter tuning performance depends on the length of the fiber paths, so, it is also possible to design the fiber lengths allowing discrete tuning over the whole filter spectral response margin. The tuning step can be arbitrarily designed changing the number of bits of the SDM.

In addition to the discrete coarse tuning, if the WDM source can slightly change the wavelength spacing between optical carriers a dynamic filter fine tuning is obtained, for instance, to select individual channels. From (3) can be seen that a slight change in $\Delta\lambda$ varies the filter spectral response. Optical sources allowing a small change in the wavelength spacing are less expensive than the broad range tuneable sources used in previous schemes.

Both fine and coarse tuning can be used jointly in order to obtain a continuously tuneable photonic microwave filter in a certain margin if the spectral gap between two adjacent coarse steps is smaller than the fine tuning margin.

Regarding the reconfiguration capabilities, it is well known from digital filter design theory [12] that the shape of the transfer function of a discrete time transversal filter can be reconfigured changing the weights (i.e. apodisating) of the time samples of the impulse response (i.e. the amplitude of the optical carriers). An alternative coarse method for reconfiguring the shape of the filter response is changing the number of signal samples or taps (i.e. optical carriers). These two reconfiguration methods modify the filter shape response but not the filter spectral features.

IV. Experimental Results

Experimental preliminary measurements have been carried out between 2 and 20 GHz in order to demonstrate the feasibility of the proposed architecture. The experimental setup is that shown in Fig. 1, where the WDM source has been implemented with two DFB lasers and a tunable laser with a wavelength spacing between optical carriers of 3.2 nm. A Mach-Zehnder modulator (MZM) with 20 GHz –3dB bandwidth was employed as external modulator. Two RF amplifiers were used to boost the RF signal from/to a vector network analyzer used to measure the filter response. In this initial demonstration, the SDM has been implemented with four path lengths of standard single-mode fiber, i.e. L_a=2.06 Km and 45, 86 and 164 meters with a dispersion parameter of roughly 16.5 ps/nm.

Fig. 3 shows the amplitude response of the proposed architecture for one arbitrary SDM state between 2 and 20 GHz employing three optical carriers (3 taps filters). The experimental results (solid line) agree quite well with the theoretical predictions (dotted line) calculated from (2).

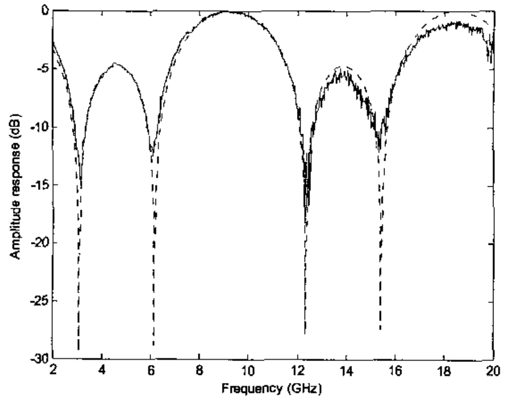

Figure 3.- Switched Photonic RF filter amplitude response. Solid line: experimental response. Dotted line: theoretical results.

On the other hand, Fig. 4 shows the filter tuning capabilities for several switching states of a 3-bits SDM. Only the experimental responses have been plotted for the sake of clarity. The filter responses have not been normalized due to the same reason. This figure shows the tuning capabilities as a function of the switch states, i.e. as a function of the fiber length traveled by the WDM signal. It may be observed that the notch shifts to lower frequencies as D_T increases.

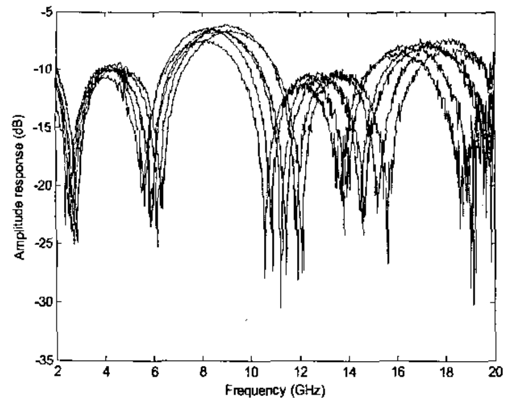

Figure 4.- Discrete filter tuning capabilities as function of the SDM state (i.e. total dispersion).

V. CONCLUSION

A novel tunable photonic RF filter architecture based on the use of a dispersion switched matrix (SDM) consisting on n 2x2 optical switches and dispersive elements has been proposed. Filter discrete tuning is achieved by changing the absolute delay path. Moreover, although not demonstrated in this paper, independent reshaping of individual filter responses is also possible by changing the amplitudes of the optical carriers or the number of taps. The filter tuning capabilities have been experimentally demonstrated. The preliminary experiments have been carried out using standard single mode fiber as dispersive element but a more compact SDM can be realized replacing these dispersive fiber with chirped fiber Bragg gratings showing the additional advantage of reducing the dispersion induced fading [13]. Although do not appear in the experimental setup used in this paper, dispersion induced fading can be a problem when higher D_T are employed. Finally, the proposed architecture does not require of the use of tunable optical sources over a huge optical margin unlike [1]-[2] which reduces the system cost.

ACKNOWLEDGEMENT

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