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Continuously Tunable Photonic Microwave Filter Based on a Spatial Light Modulator

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Abstract: An optical microwave filter architecture which can be continuously tuned is proposed and demonstrated. The architecture is based on a nematic liquid crystal spatial light modulator in parallel configuration and has the potential to control a large number of taps. Proof-of concept experimental results are provided.

***Keywords**:* Microwave photonics; photonic microwave filters.

1. INTRODUCTION

Since the early 80's the study of photonic microwave filters has attracted the interest of many research groups [1] due to its 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. The research has been focused on the implementation of high performance filter responses [2-4], techniques to obtain positive and negative taps [5-6] as well as architectures showing tunable and reconfigurable microwave optical filters [7-8].

To obtain high-Q filter responses a large number of taps is needed. Many filter architectures use as many optical carriers as filter taps to avoid coherent interference. Since using independent sources practically limits the number of taps, the use of multiwavelength sources or the spectrum slicing of broadband sources has been proposed [9]. Using this kind of sources, discrete tuning of the filter response can be obtained but continuous tuning is more difficult [1]. In this Letter, a photonic microwave filter which allows the continuous tuning of the response using a spatial light modulator is proposed. Additionally, the architecture has the potential to control a large number of taps.

2. PRINCIPLE OF OPERATION

The electrical frequency response of a transversal filter can be expressed as

$$H(f_{RF}) = \sum_{n=1}^{N} a_n e^{-i(n-1)2\pi f_{RF} T} \tag{1}$$

where, N is the number of taps, a_n is the amplitude of the n tap, f_{RF} the electrical frequency and T the basic delay between taps [1]. From (1) it can be deduced that a progressive phase between elements leads to a frequency response shift, which can be used to tune the RF bandpass position and also to achieve negative taps.

The proposed architecture is based on providing a phase shift at each sample by means of a nematic liquid crystal spatial light modulator in parallel configuration PA-NLC SLM [10]. The polarization component of light parallel to the optical axis of the PA-NLC SLM experiences a different refraction index depending on the applied voltage. On the other side, the polarization component of light perpendicular to the optical axis undergoes a constant refraction index. Therefore, if the optical carrier is aligned with one axis and the sideband with the other one, the phase of the RF signal can be continuously controlled. Moreover, this feature can be used to control the amplitude of the incident signal [11-12]. This amplitude control provided by the PA-NLC SLM can be used to achieve continuous tuning in some architectures [13].

Due to the pixelated PA-NLC SLM structure a correspondence between each pixel of the PA-NLC SLM and each tap can be achieved allowing the control of filters with large number of samples.

A differential group delay module (DGD), which provides group delay between two linear orthogonal polarization states, can be used to cross-polarize the optical carrier and its sideband. It can be explained mathematically in the following way: if light is launched to a birefringent material, the optical phase of the beam at the output of the device depends on wavelength,

$$\varphi = \frac{2\pi d(n_e - n_o)}{\lambda}. \tag{2}$$

Therefore, the phase shift between two wavelengths spaced a certain frequency (f_{RF}) when they are travelling through a birefringent material is given by

$$\Delta\varphi = 2\pi f_{RF} DGD, \tag{3}$$

where DGD is the differential group delay introduced by birefringence. Depending on the wavelength of the incident beam the birefringent material provides different polarization states at the output. Taking into account (2) and the fact that this device can be represented by the Jones formalism as

$$M = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix}, \tag{4}$$

it can be deduced that in order to obtain linear orthogonal polarizations between the optical carrier (f_0) and the sideband (f_0+f_{RF}), i.e. to obtain a phase shift equal to π, the polarization state of the amplitude modulated optical carrier has to be linear at 45° with the material axis and the DGD needed is $1/(2f_{RF})$. From (3) it can be seen that the phase shift generated by the DGD is proportional to frequency. Therefore, at even multiples of the design frequency, the optical carrier and its sideband are parallel and the filter response reminds unchanged around this frequency.

A polarizer at 45º has to be placed after the PA-NLC SLM in order to combine the carrier and the sideband in the same state of polarization since two orthogonal signals do not beat at the photodiode.

The range of phase control of the electrical signals (taps) is the same provided by the PA-NLC SLM if single sideband amplitude modulation (SSB) is used (i.e. a PA-NLC SLM with a phase control range of 3π provides microwave phase shifts up to 3π), if dual sideband is used instead of SSB the control of the microwave signal phase is very limited.

Taking into account the state of polarization of the signal at the DGD output, the phase shift as a function of frequency can be calculated by means of the Jones formalism as

$$\varphi_{RF} = \arctan\left(\frac{-2E_s^yE_c^y Sin(\phi_s^D-\phi_c^D)Sin(\beta)^2+\left(-E_s^yE_c^x Sin(\phi_s^D-\phi_{SLM})+E_s^xE_c^y Sin(\phi_c^D-\phi_{SLM})\right)Sin(2\beta))}{2E_s^xE_c^x Cos(\beta)^2+\left(2E_s^yE_c^y Cos(\phi_s^D-\phi_c^D)Sin(\beta)^2+(E_s^yE_c^x Cos(\phi_s^D-\phi_{SLM})+E_s^xE_c^y Cos(\phi_c^D-\phi_{SLM})\right)Sin(2\beta)}\right)$$

(5)

where, $\phi_{S,C}^D$ and ϕ_{SLM} are the phase introduced by the DGD and the PA-NLC SLM to the carrier and its sideband, respectively; $E_{S,C}^{x,y}$ is the amplitude of the optical carrier and the sideband; and β is the polarizer angle.

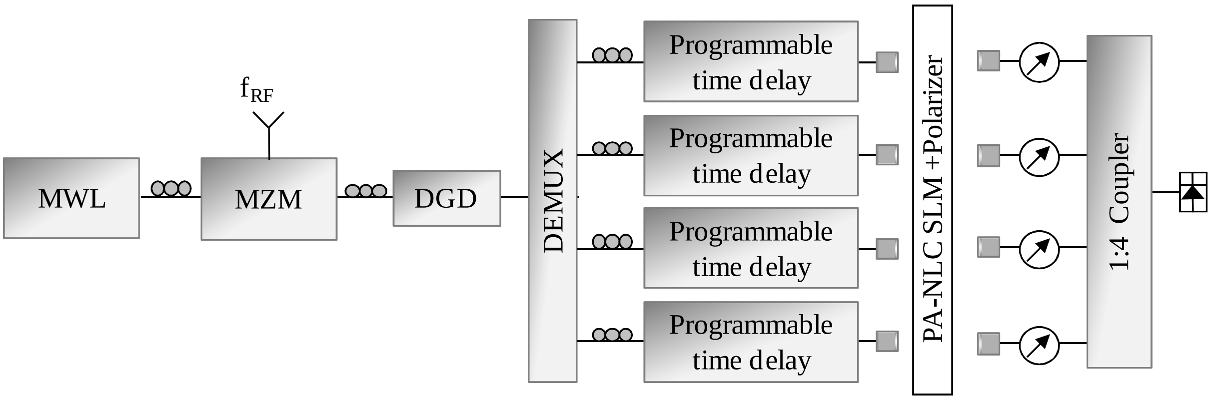

Fig. 1.- Block diagram of the filter proposed base on a PA-NLC SLM.

The block diagram of the filter architecture is depicted in Figure 1. Firstly, a multiwavelength laser (MWL) is amplitude modulated using a dual-drive MZM to generate SSB modulation [14]. Secondly, the signals are launched to a DGD module, which cross-polarizes the optical carriers and the sidebands. Next, they are demultiplexed using a demux and are split in branches of different length in order to achieve the progressive time delay between taps. By means of fiber collimators, the carriers and its sidebands are launched to free-space where a PA-NLC SLM is used to control the phase of each sample. Then, the beams are coupled from free-space into single-mode fibre and the amplitude of each channel is controlled by a Variable Optical Attenuator (VOA). Finally the signals are photodetected. Polarization controllers are used to provide the correct state of polarization to the MZM, the DGD, and the PA-NLC SLM.

After the PA-NLC SLM used for phase control, a second modulator and a polarizer could be used to control the amplitude of the optical signal of each pixel (instead of the VOAs), allowing the optical tapering of the amplitudes of the samples. Another option is the use of a single spatial light modulator with the capability of phase and amplitude control simultaneously (which are commercially available).

Using this technique, coarse discrete tuning of the filter response can be achieved, by varying the length of the branches, for instance using programmable optical delay lines [15].

Once a certain filter response is chosen by selecting the corresponding progressive time delay between taps, it is possible to introduce dynamic fine continuous tuning capabilities by means of the PA-NLC SLM [16].

3. EXPERIMENTAL RESULTS

Several measurements were carried out to show the feasibility of the architecture. The experimental set-up is depicted in Figure 2. The multiwavelength source was implemented using four independent lasers (1550.92, 1550.12, 1549.32, and 1548.51 nm), a coupler and four polarization controllers.

The signals were amplitude modulated using a DD-MZM (IL = 9 dB at QB) fed by the signal generated by a RF vector network analyser. A fixed DGD module (IL = 2 dB) with a differential group delay of 62.5 ps was used in order to obtain linear orthogonal polarizations between two wavelengths spaced 8 GHz corresponding to the optical frequency separation between the optical carrier and the sideband (i.e. to provide the filter tunability around 8 GHz). Next, the signals were amplified by an Erbium Doped Fiber Amplifier (EDFA) and an optical demultiplexer (IL = 1 dB) was used to split the signals in four channels. Then, optical delay lines (ODL) were introduced in each one of the four branches to generate the progressive time delay between samples. After the ODLs (IL = 1.5 dB), polarization controllers were placed to adjust the polarization state of the optical signals to the axis of the PA-NLC SLM. To control the phase of the RF signals, a PA-NLC SLM (IL = 3 dB, including collimation loss) and a polarizer were used. The beams were collimated up to 11 cm by means of a set of 4x4 collimators. To control the amplitude of the optical signals a set of VOAs (IL = 1 dB) was included in the setup.

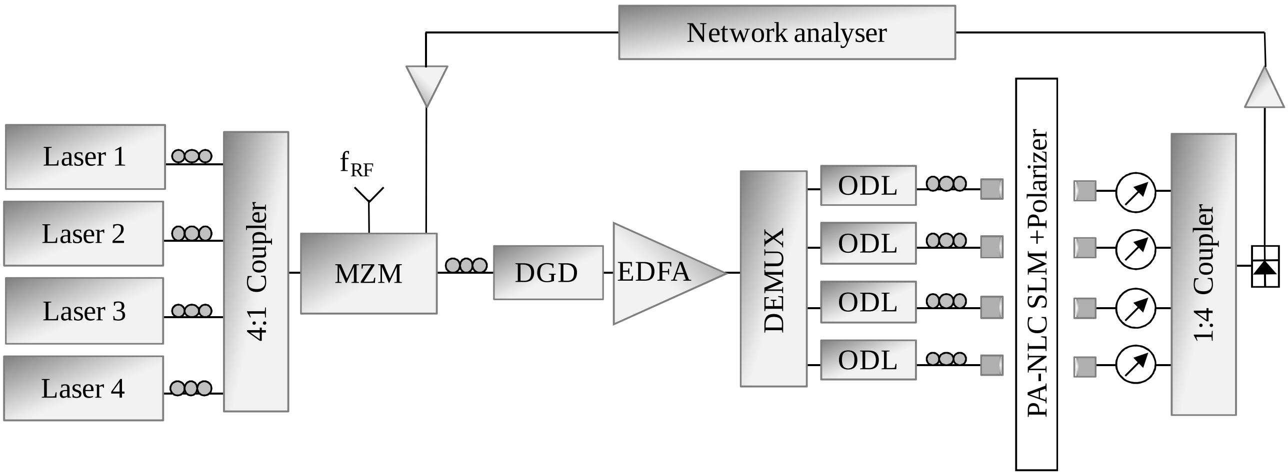

Fig. 2.- Experimental setup using four optical carriers.

In Figure 3, the filter tuning capability is demonstrated. Several filter responses corresponding to a progressive time delay equal to 250 ps and different progressive phase shifts between taps (0º, 10º, 25º, 45º and 90º) are depicted. As can be seen the amplitude response of the filter can be tuned around 8 GHz as predicted by the theory.

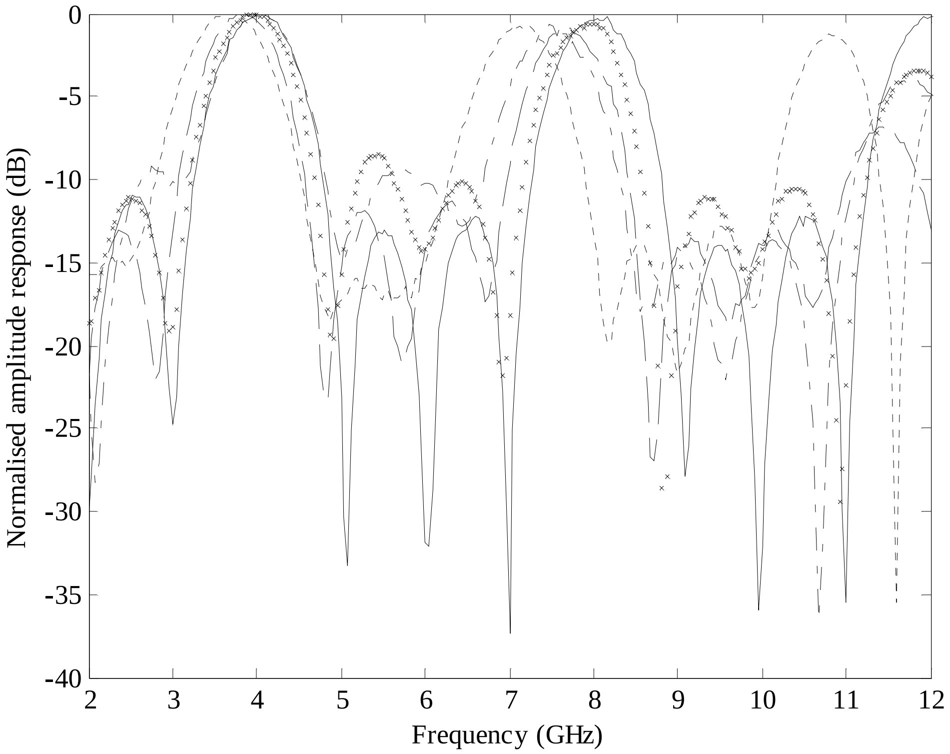

Fig. 3.- Comparison of the filter responses for different values of phase shift: solid 0º, cross 10º, dashed 25º, dot-dashed 45º, dotted 90º.

Figure 4 shows a good agreement between the experimental results and the theoretical predictions for a phase shift equal to 10º.

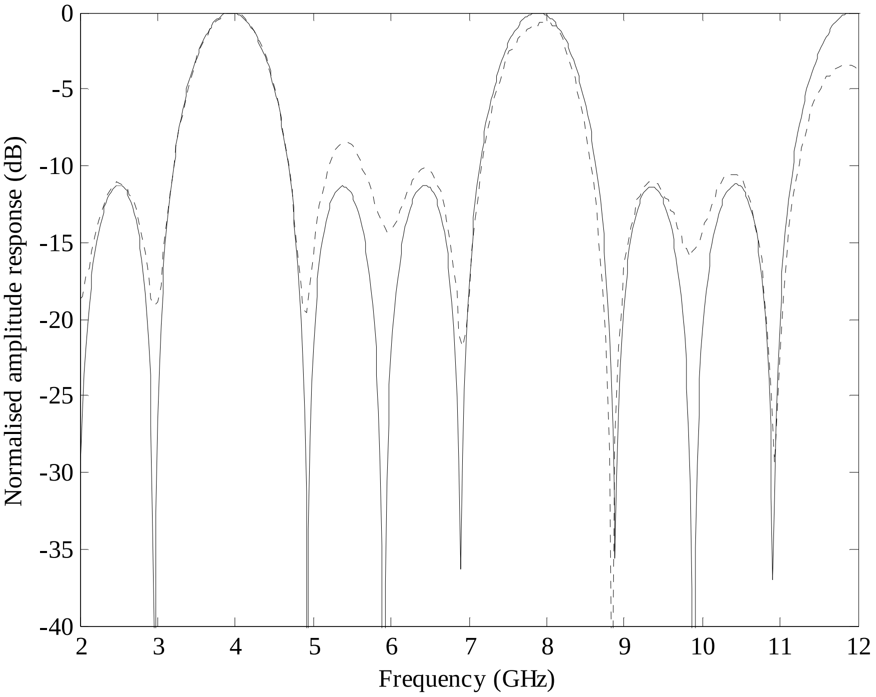

Fig. 4.- Filter response for a phase shift of 10º. The dashed curve corresponds with measurement and the solid one with theory.

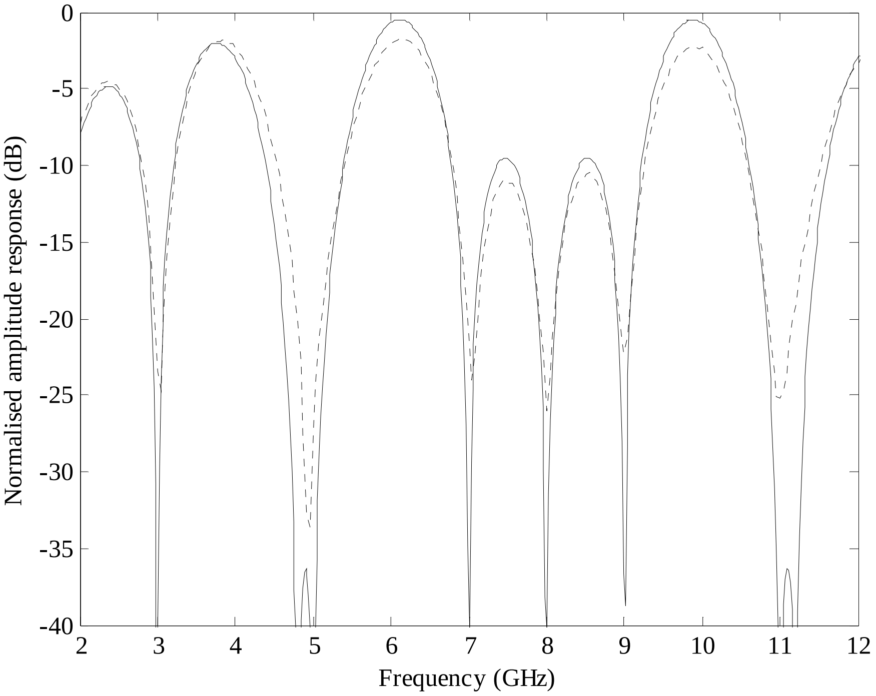

Fig. 5.- Filter response when the phase of the first and third tap were 0º and 180º for the second and fourth one. The dashed curve corresponds with measurement and the solid one with theory.

Finally, in order to show the feasibility of implementing negative taps, the filter response was measured when the phase shift introduced by the PA-NLC SLM was 0º for the first and third tap and 180º for the second and fourth one (i.e. corresponding to the amplitude distribution of the taps [1 -1 1 -1]). The experimental result agrees quite well with theory as can be seen in Figure 5.

4. CONCLUSION

A microwave filter implemented optically and whose amplitude response can be continuously tuned has been proposed. Tunability is achieved by means of a PA-NLC SLM. On the other side, the technique has the potential to control a large number of samples as well as providing reconfiguration capability if spatial light modulators with amplitude and phase control are used. Preliminary experimental results validating the feasibility of the technique have been provided.

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